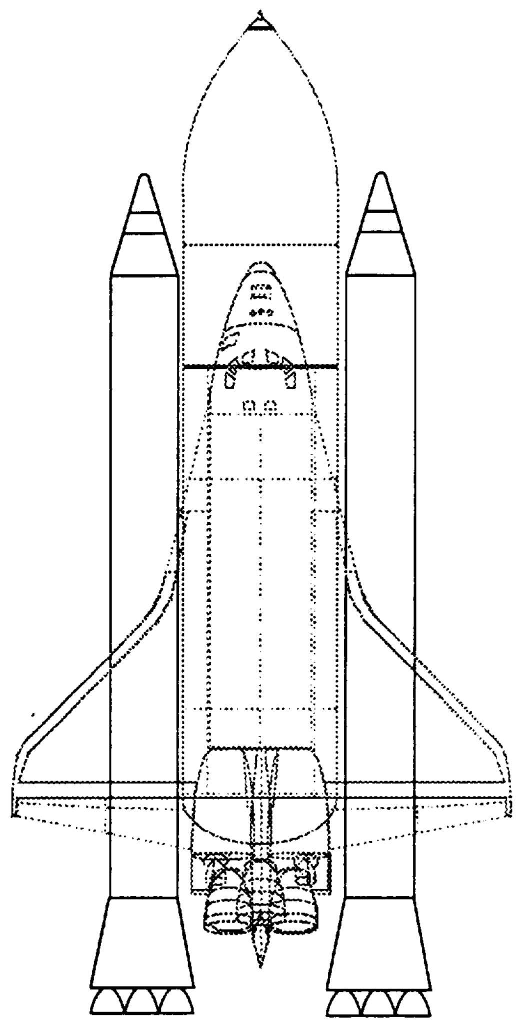
NAS8-37136

March 1989

Appendix A
Stress Analysis Report for the Pump-Fed and Pressure-Fed Liquid Rocket Booster

Liquid Rocket Booster (LRB) for the Space Transportation System (STS) Systems Study



(NASA-CR-183787-App-A) LIQUID ROCKET BOOSTER (LRB) FOR THE SPACE TRANSPORTATION SYSTEM (STS) SYSTEMS STUDY. APPENDIX A: STRESS ANALYSIS REPORT FOR THE PUMP-FED AND PRESSURE-FED LIQUID ROCKET BOOSTER (Martin   N90-28601

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MANNED SPACE SYSTEMS

Stress Analysis Report for the Pump-Fed and Pressure-Fed Liquid Rocket Booster

Appendix A

Pump Fed Stress Analysis

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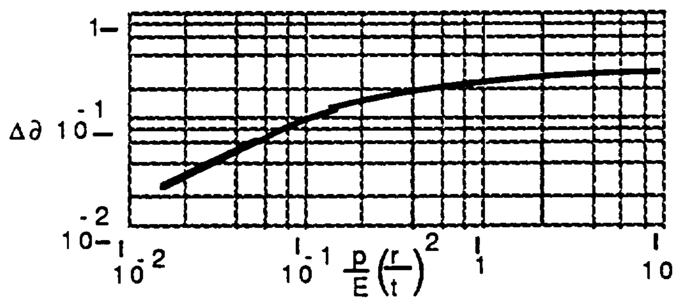
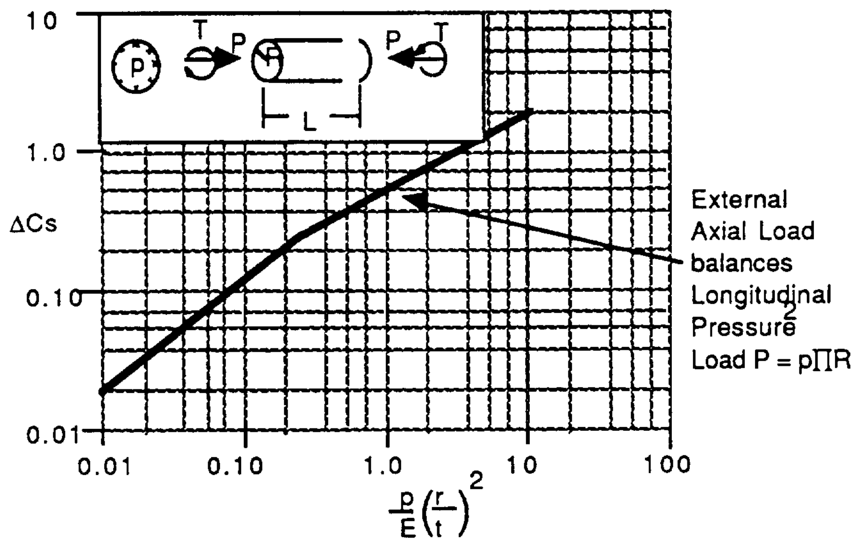
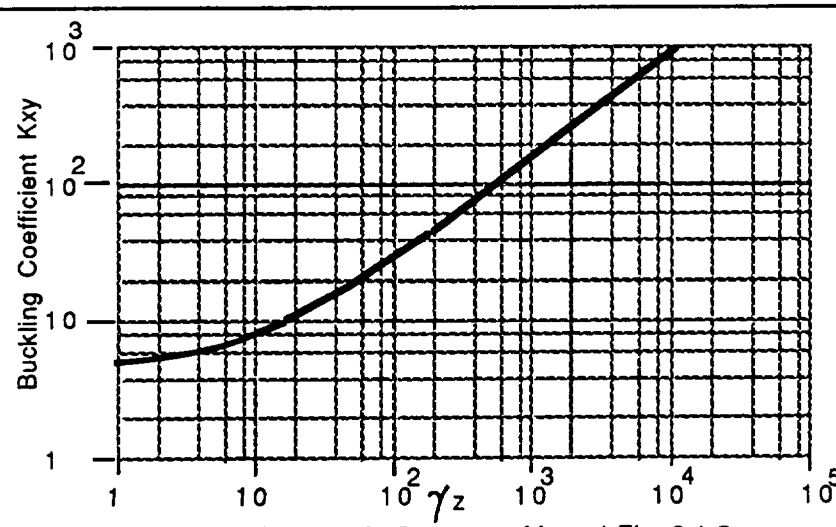
Buckling Analysis Methodology (Cont'd)



Astronautic Structures Manual Fig. 3.1-2:
Increase in axial-compressive Buckling Stress Coefficient of Cylinders resulting from Internal Pressure

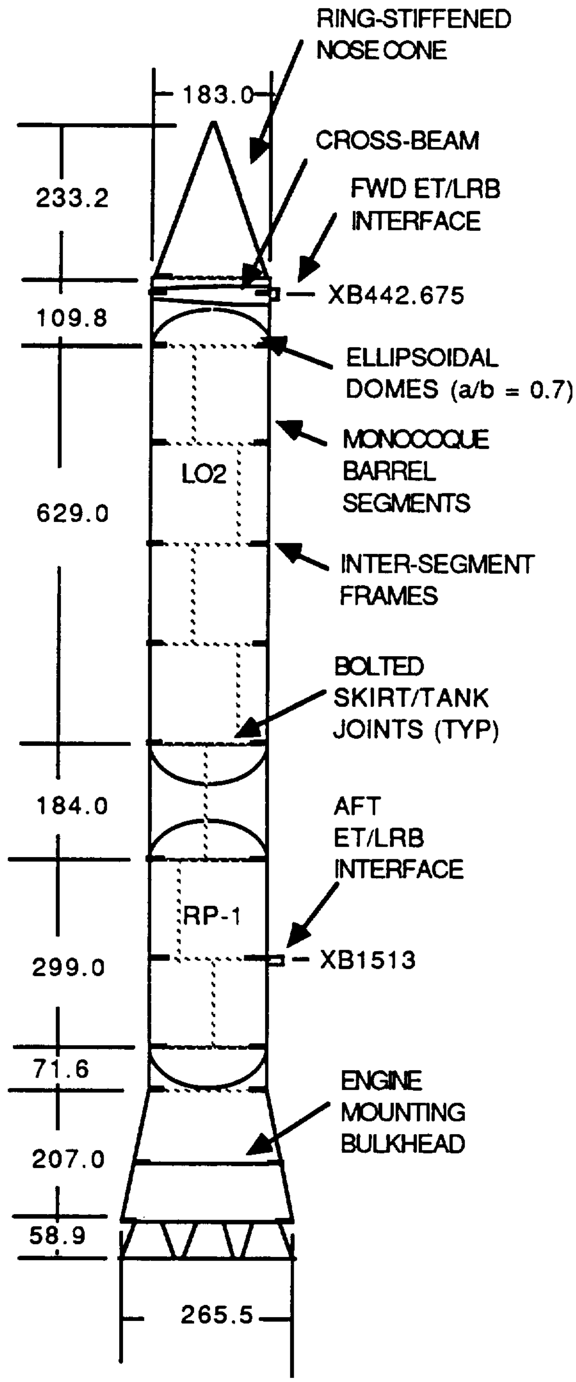


Increase in Torsional Buckling Stress Coefficient of Cylinders due to Internal Pressure.
Ref: Figure on Page 9.22.09 of Rockwell International Structures Manual



Astronautic Structures Manual Fig. 3.1-5:
Buckling Coefficients for Simply Supported Isotropic Circular Cylinders subjected to torsion.

Pump-Fed Stress Analysis



Structural Arrangement

Pump-Fed Stress Analysis

Basic Data

Criteria (Ref: LRB CEI Specification - Rev 1, April 1988):-

Safety Factors:

Ultimate = 1.25 (static and well-defined loads)
1.40 (dynamic and aerodynamic loads)

Proof = 1.10 (Min.)

Frame minimum stiffness requirements were obtained from Shanley - 'Weight-Strength Analysis of Aircraft Structures' - Equation 3.5

$(EI) = \frac{C_f MD^2}{L}$ where:

E = Frame Modulus
I = I of Frame Cross-Sect
L = Frame Spacing
D = Cylinder Diameter
C = 1/16000
M = fl/R
f = Max Cyl Stress from Bending + Axial Loads

The following values were taken as the best preliminary estimates available at time of analysis

Properties of Weldalite TM 049:

	R.T.
Ftu (KSI)	100
Fty (KSI)	95
Weld Fall (KSI)	45.0
E 1000 (KSI)	11.3

Property Variation With Temperature						
$^{\circ}F$	-297	R.T.	200	250	300	320
% R.T.	1.15	1.0	.95	.92	.90	.88

Ullage Pressures:

Pump Fed - P(Ullage) MIN = 45 PSI(LO2 Tank)
= 35 PSI(RP-1 Tank)
P(Ullage) MAX = 60 PSI
Relief Valve Allowable = 10% Net = 66 PSI

Pump-Fed Stress Analysis

Buckling Analysis Methodology

The Pump-Fed LRB has maximum N(x) kips/in (i.e. longitudinal loads) from combined bending plus axial compression, with the bending effect predominating at the maximum values. Transverse and torsional shear kips/in from applied loads are small and significant shears arise only in localized areas, e.g. in the Aft Skirt adjacent to longerons and thrust posts, and in the padded area of the LO2 Tank.

Tank buckling is checked by the method of NASA-MSFC Astronautics Structures Manual Sect C 3.0, as used in the E.T. LO2 Tank analysis. Cylinder length is taken as the distance between frames. Ullage pressures causing relief to the compressive N(x) are taken as unfactored. Ullage plus head pressures providing stability assistance to the tank wall are factored by 0.5. The hoop load component N(y) is ignored for stability analysis, hence the only significant loads are N(x) and N(xy), and the latter only in certain areas as indicated above.

$Nx(crit) = Et(K_1\partial + \Delta\partial)$

$K_1 = 1/\sqrt{[3(1-\mu^2)]}$

$= .6116$ for $\mu = .33$

E = Modulus (lb/sq. inch)
t = shell thickness (inches)
R = cylinder radius (inches)
L = Length (inches)
$\mu = .33$

$\partial = 1.0 - K_2(1 - e^{-\phi})$

$\phi = (\sqrt{R/t})/16$

$K_2 = .901$ for cylinders in axial compression

$= .731$ for cylinders in bending

Since loading is predominantly bending in the higher loaded areas, K_2 is taken as:

$(.901 + .731)/2 = .816$

$\Delta\partial$ (Pressure Enhancement Factor for pressurized shell) is taken from Fig. 3.1-2 of the ASM

$Z = (L^2/RT)\sqrt{(1-\mu^2)}$ $\qquad \gamma^{3/4} = .67$ i.e. $\gamma = .5863$

For shear:

$$N_{xy}(crit) = \frac{1.25\,\pi^2 K_{xy}}{12(1-\mu^2)} \frac{Et^3}{L^2} + \frac{Et^2(\Delta Cs)}{R}$$

Kxy is taken from Fig 3.1-5 of the ASM and Pressure Enhancement Factor ΔCs from Fig page 9.22.09 of Rockwell International Structures Manual.

The 1.25 enhancement is included as in the E.T. analysis referenced above.

Pump Fed Stress Analysis

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Pump-Fed Stress Analysis

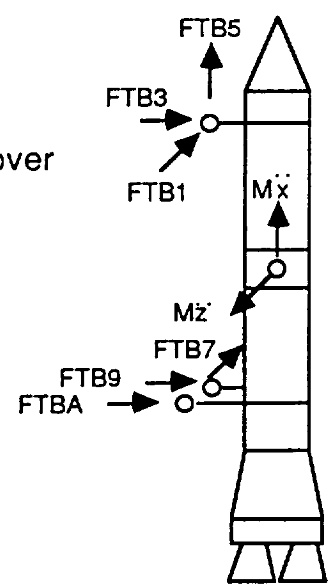
Loads = KIPS (ULT)
Loads on L.H. side of vehicle are shown
Loads on R.H. side are identical

FTB	3D REV4/REV5 LOADS		PRELIMINARY LRB STUDY LOADS - REV1 PUMP FED				PRESSURE FED				SRB RIGID BODY ANAL	
	MAX	MIN	MAX		MIN		MAX		MIN		MAX	MIN
1	285.4	-288.8	3	247.5	3	-172.5	8	252.5	8	-167.5	296.3	-123.8
3	296.5	-122.3	3	220.0	3	-60.0	8	200.0	8	-80.0	225.0	-55.0
5	223.3	-2205.6	-	-	5	-2069.0	-	-	10	-2066.0	-	-
7	346.1	-319.8	3	205.5	3	-130.5	8	210.5	8	-125.5	172.0	-164.0
9U	302.1	-248.4	3	157.0	3	$\boxed{-347.0}$	8	160.8	8	$\boxed{-343.3}$	154.0	$\boxed{-350.0}$
A	414.0	-353.8	3	197.0	3	-167.0	8	213.3	8	-150.8	196.0	-168.0

Load Condition Key:

1 - Pump Fed - On Pad - Gravity Loads Only
2 - Pump Fed - On Pad - Gravity + SSME's - Max Pitchover
3 - Pump Fed - Lift Off
4 - Pump Fed - MaxQ
5 - Pump Fed - Boost Ascent (BA)

Conditions 6 through 10 are for the Pressure-Fed vehicle.



Interface Loads - Ultimate

Ultimate Bending Moment & N(X) Diagrams

A loadset of 5 conditions is used for LRB design:
1) On Pad
2) On Pad; Max Pitchover
3) Lift-Off (L/O)
4) Max Q
5) Boost Ascent (BA)

Design moments and end loads come from conditions 2 & 5 .

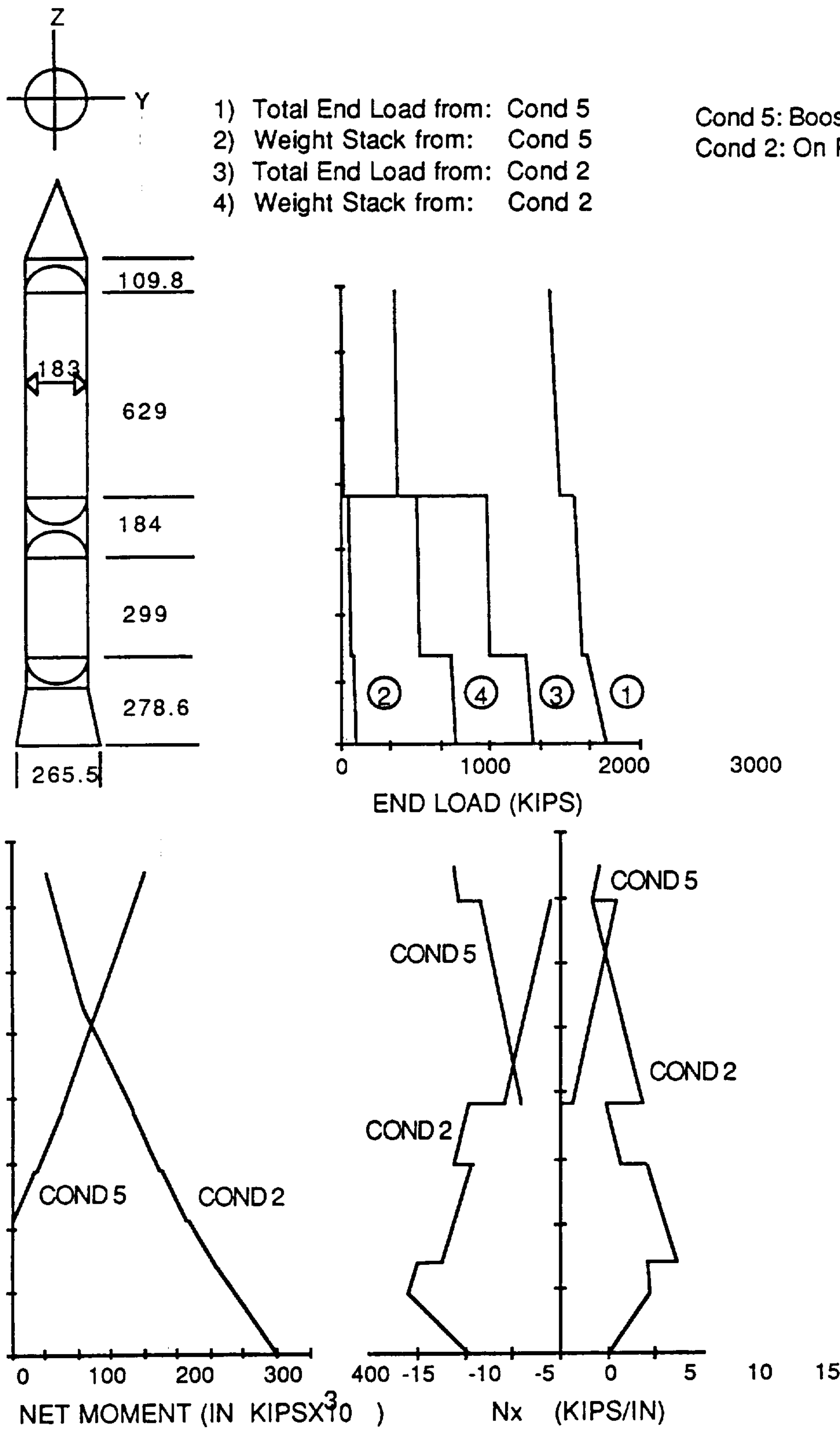
Max Pitchover produces large cantilever bending moments about the base in the tie-down position. BA produces large moments at the forward ET attachment point due to the offset from the LRB centerline of the LRB thrust reaction, which is greatest at BA.

An ullage pressure minimum value of 45 psi is used to obtain max compressive N(x) values and a maximum value of 66 psi to obtain the max tensile N(x) values.

The maximum moments shown are the resultants of the M(y) and M(z) values at the given station, and hence their angular position varies with station along the tank. Also, max moments from the different conditions have different angular positions at any given station.

Values shown are ultimate, except for 1 g Weight Stack values.

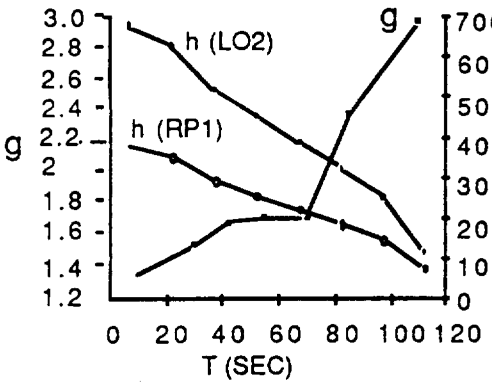
Pump-Fed Stress Analysis

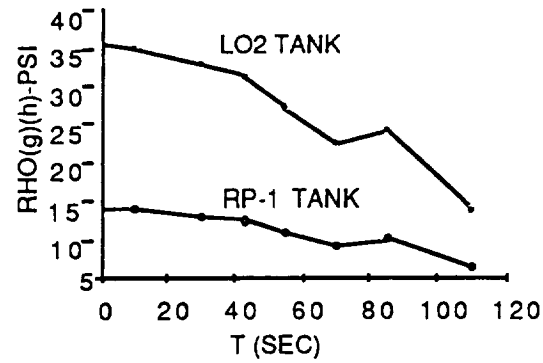


Ultimate Bending Moment & N(X) Diagrams

JC2-LRB2-2-3

Pump-Fed Stress Analysis





h = Height of liquid above dome bottom (in.)
RHO = Liquid Density (lb/cu. in.)
h = Liquid height above tank bottom (in.)
g = 32.2 ft./sec./sec.

The above graphs show that the maximum values of rho(g)(h), i.e. head pressure at tank bottom, occur at Lift-Off

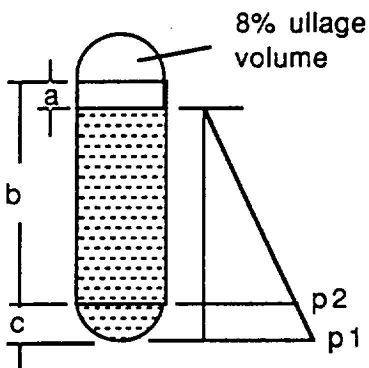


Fig 1

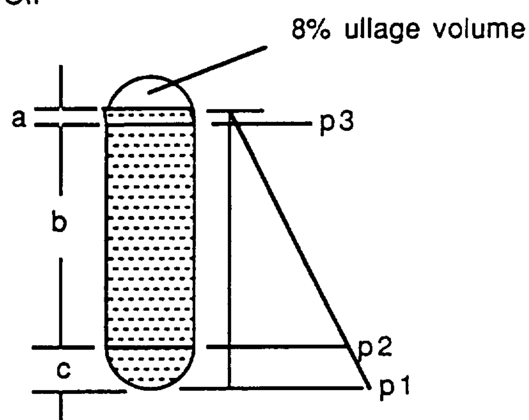


Fig 2

Values at Lift-Off

	Pump-Fed	
	LO2 Tank	RP1 Tank
Ref. Fig.	1	2
a (in)	14	12
b (in)	629	299
c(in)	64	64
rho (lb/in^3)	.0411	.0293
g $\triangle$1	1.247	1.247
p1 (psi)	34.8	13.7
p2 (psi)	31.5	11.4
p3 (psi)		0.4

The above table gives Limit values of Head Pressure P at stations shown

$\triangle$1 From Loadsets of 3/21/88 & 3/25/88

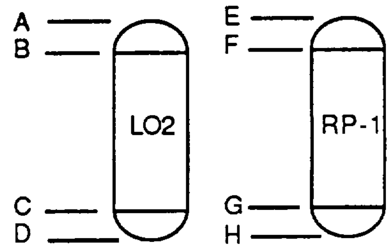
JC2-LRB-2-6

Tank Head Pressures

Pump-Fed Stress Analysis

2 conditions are considered for maximum tank pressure:-
1) Lift-Off, where tank head pressures are maximum
2) Pre-Release, where tank head pressures are virtually zero, and only ullage pressure is considered, but wall temperatures are maximum, and material strength properties have suffered maximum reduction.

Pump-Fed Ullage Pressure (Limit) = 66 psi
S.F. = 1.25
LO2 density = .0411 lb/cu. in.
RP1 density = .0293 lb/cu.in.



Lift-Off

SECT	P	T	NOTE	K	P(EQ)
A	82.5	RT	1	1.0	82.5
B	82.5	RT	1	1.0	82.5
C	121.9	-297	2	1.15	106.0
D	126.0	-297	2	1.15	109.6
E	82.5	RT	1	1.0	82.5
F	83.0	RT	3	1.0	83.0
G	96.7	RT	3	1.0	96.7
H	99.6	RT	3	1.0	99.6

Pre-Release

SECT	P	T	NOTE	K	P(EQ)
A	82.5	300	3	.9	91.7
B	82.5	300	3	.9	91.7
C	82.5	RT	3	1.0	82.5
D	82.5	RT	3	1.0	82.5
E	82.5	300	3	.9	91.7
F	82.5	300	3	.9	91.7
G	82.5	200	3	.95	86.8
H	82.5	200	3	.95	86.8

P = Ult Pressure (Ullage + Head) - PSI
T = Wall Temp (Deg. F)
K = Material Strength Temperature Factor
P(EQ) = P/K

Notes:-
1 Pressurized by ambient temperature helium until L/O
2 Propellant temperature
3 Estimated values

<u>Max Ultimate Pressures</u>

Pump-Fed Stress Analysis

The tanks are proofed by water at room temperature. The values shown assume the tanks are suspended at the upper dome/barrel intersection level since this slightly reduces the required pressures compared with base mounting. The required proof pressures for each tank are set by the pressure required to proof the lower dome/barrel circumferential weld against longitudinal loads. The values shown for barrel N(x) proof pressure are those values of uniform internal pressure which would produce the same values of longitudinal load/in in the barrels as the proof head pressures with the tanks suspended as shown. Due to the pressures required on the above basis, the tanks are overproofed in the hoop direction. Only the pressure loading is shown in the diagrams. Pinch loads on the Aft LRB Support frame are not considered at this stage, and their simulation by mechanically applied loads may alter the scheme shown.

LOC	P REQ (PSI)	TO PROOF	FOR CONDITION	P(PROOF)		F(PROOF) MEMBRANE		F(PROOF) WELD	
				LONG WELD	CIRC WELD	LONG	HOOP	LONG	HOOP
A	80.7	DOME WELDS	P(ULLAGE)	128.9	128.9	70.20	7020	33.70	33.70
B	150.1	CIRC WLD AT B	N(X)#5	131.3	156.8	14.31	23.96	14.31	23.96
C	156.8	CIRC WLD AT C	N(X)#2	155.1	156.8	14.31	28.31	14.31	28.31
D	96.5	DOME WELDS	P(TOT)#3	157.6	157.6	85.83	85.83	41.20	41.20
E	80.3	DOME WELDS	P(ULLAGE)	223.9	223.9	91.45	91.45	43.04	43.04
F	182.1	CIRC WLD AT F	N(X)#2	226.3	239.3	21.84	41.30	21.84	41.30
G	239.3	CIRC WLD AT G	N(X)#2	237.6	239.3	19.85	39.42	19.85	39.42
H	87.7	DOME WELDS	P(TOT)#3	240.0	240.0	92.26	92.26	43.57	43.57

PARENT METAL F(YIELD) = 95 KSI
WELD F(ALL) = 45 KSI

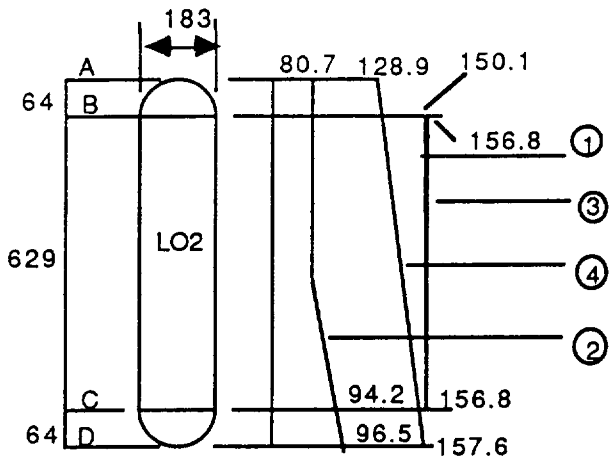
COND #2 = ON PAD; MAX PITCHOVER
COND #3 = LIFTOFF
COND #5 = BOOST ASCENT

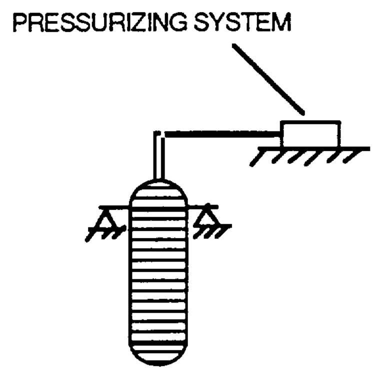
STRESSES IN KSI
PRESSURES IN PSI

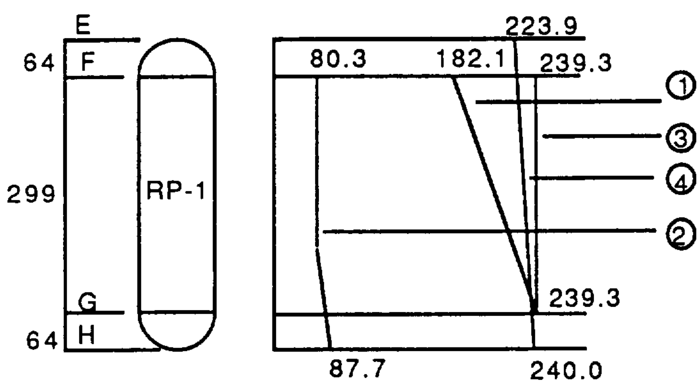
POSITION	t (MEMBRANE)	t (WELD)
A	.12	.25
B	.5	.5
C	.5	.5
D	.12	.25
E	.16	.34
F	.5	.5
G	.55	.55
H	.17	.36

<u>Proof Pressure</u>

Pump-Fed Stress Analysis







P3 IS THE EQUIVALENT UNIFORM INTERNAL PRESSURE TO PRODUCE THE SAME NX IN THE TANK WALL AS THE ACTUAL HEAD PRESSURE (RHO)(G)(H) WITH THE TANK SUSPENDED AS SHOWN

PROOF PRESSURES ARE SET BY THE REQUIREMENT OF CURVES 3 TO MEET CURVES 1 AT LEVEL C (LOXTANK) & LEVEL G (RP1 TANK)

1 REQU'D PROOF PRESSURE (BARREL - NX)
2 REQU'D PROOF PRESSURE (BARREL NY & DOMES)
3 PROOF PRESSURE (BARREL NX)
4 PROOF PRESSURE (BARREL NY & DOMES)

PROOF WITH WATER AT ROOM TEMPERATURE. TANKS SUSPENDED AT LEVEL B (LOXTANK) & LEVEL F (RP1 TANK)

PROOF FACTOR = 1.10
PRESSURES = PSI

REQUIRED PRESSURES DERIVED ON ROOM TEMPERATURE EQUIVALENTS OF APPLIED LOADS

Proof Pressure

Pump-Fed Stress Analysis

Barrels

The Pump-fed tank barrels consist of 4 cylindrical segments for the LO2 tank and 2 segments for the RP-1 tank , each segment consisting of curved panels joined by longitudinal welds. Frames are welded between each barrel segment to maintain tank circularity.
Shell thickness is 0.5 in except for a localized area on the y-axis in the LO2 tank below the forward attachment to the intertank where the forward E/T attachment FTB5 (axial direction) loads are concentrated into the barrel, and the lower segment of the RP-1 tank where buckling considerations require $t = 0.52$.

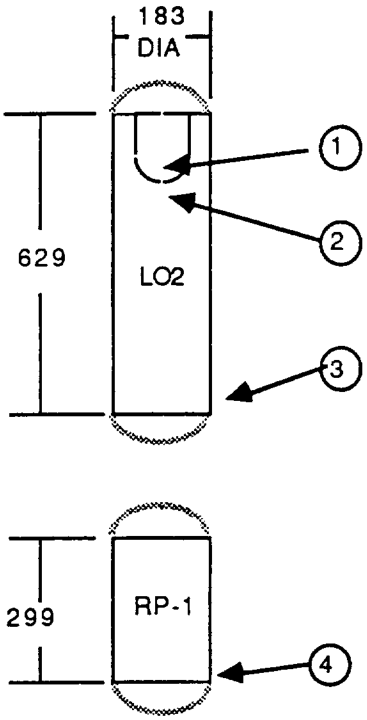
Welds are the same thickness as the shell, i.e. raised weld lands are not required on 0.5 inch thickness.

Barrels are loaded by 2 principal conditions which induce high compressive + bending loads i.e. the On Pad - Max Pitchover and Boost Ascent conditions.

The pitchover loads are affected by the LRB cantilever bending stiffness. To avoid significant load increases, the LRB bending stiffness was maintained approximately equal to the SRB bending stiffness. A $t = 0.5$ met this requirement and also gave satisfactory shell buckling margins over most of the shell area. Regions requiring greater t are noted above.

.
The buckling analysis was carried out using standard cylinder buckling analysis (i.e.E.T.LO2 tank method - conservative version).
Axial tension induced by the design conditions is not design critical.
Tension loads induced during proof test are considered on the sheets dealing with proof test.

Pump-Fed Stress Analysis



t(WELD) = t(PLATE)

COND #2 = ON PAD;MAX PITCHOVER
COND #5 = BOOST ASCENT

VALUES CORRECTED TO ROOM TEMP EQUIVALENTS

PARENT F(ALL) = 100 KSI (ULT)
95 KSI (YIELD)
WELD F(ALL) = 45 KSI

PROOF: S.F. = 1.1
ULT. : S.F. = 1.25 - STATIC COMPONENT
1.4 - DYNAMIC COMPONENT

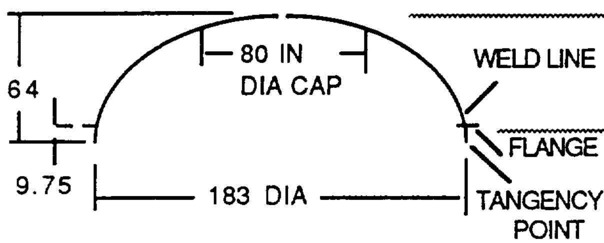
HOOP TENSION STRESS (PROOF)					
LOC	PRESSURE (PSI)	t(IN)	f(KSI)	M.S. PARENT	M.S. WELD
3	155.1	0.5	28.3	> 1.0	0.59
4	226.3	0.55	39.4	> 1.0	0.14

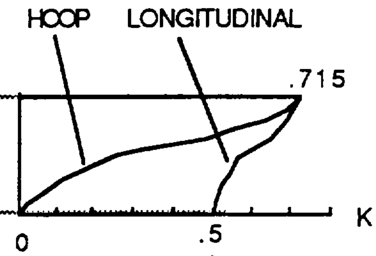
WALL BUCKLING(ULT)					
LOC	COND	Nx KIPS/IN	Nxy KIPS/IN	t(IN)	M.S.
1	# 5	-21.47	-0.46	0.7	0.14
2	# 5	-10.92	0.38	0.5	0.14
4	# 2	-12.34	-	0.55	0.20

~~Pump-Fed~~ Barrels

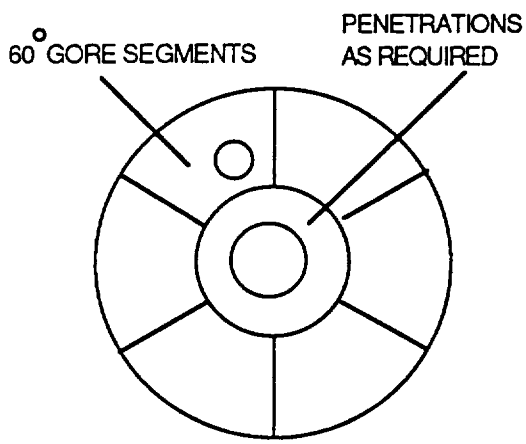
Pump-Fed Stress Analysis

Pump-fed domes are elliptical, with a height to radius ratio of 0.7 to minimize overall LRB length. They consist each of 6 gore segments and an 80 inch diameter dome cap, with penetrations in the cap as required. Welds and weld lands are approximately twice as thick as the membrane, as dictated by parent and weld metal strengths.





For Elliptical Domes
f = K P R / t
P = PRESSURE
R = RADIUS
t = THICKNESS



NO YIELD AT PROOF:

MEMBRANE F(ALL) = 95 KSI
WELD F(ALL) = 45 KSI

PROOF S.F. = 1.1

DOME	M.S. MEMBRANE	M.S. WELD
LO2 UPPER	0.35	0.33
LO2 LOWER	0.11	0.09
RP-1 UPPER	0.04	0.04
RP-1 LOWER	0..03	0.03

DOME	P(DESIGN) PSI	COND	t(MEMBRANE IN	t(WELD) IN	f(MEMBRANE KSI	f(WELD) KSI
LO2 UPPER	128.9	PROOF	.12	.25	70.20	33.70
LO2 LOWER	157.6	PROOF	.12	.25	85.83	41.20
RP-1 UPPER	223.9	PROOF	.160	.34	91.45	43.04
RP-1 LOWER	240.0	PROOF	.170	.36	92.26	43.57

~~Pump-Fed~~ Domes ~~Data~~

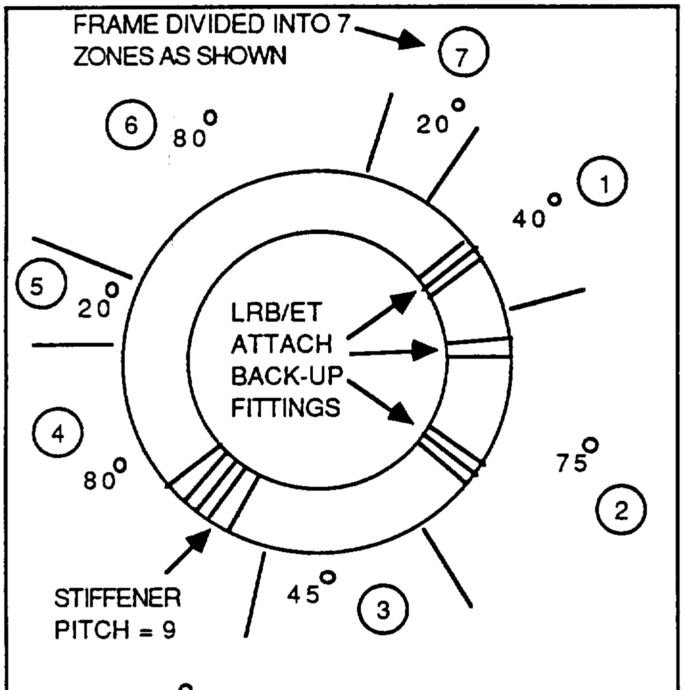
JC2-LRB-4-5

Frame XB1513

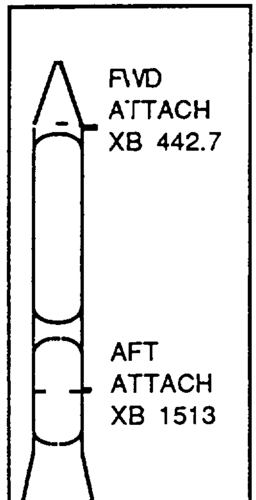
The XB1513 frame carries the aft LRB/ET attachment loads into the LRB structure. Construction follows that of the ET XT 2058 frame, i.e. built-up chord/web with web stiffeners and back-up fittings at the ET attachment points. The frame is divided into 7 segments for design purposes. Section dimensions for each segment are tabulated on the view sheet.

Maximum LRB/ET interface loads arise during the Lift-Off condition and their effects superimpose on the tension induced in the frame by ullage and head pressure in the tank. The frame internal loads are obtained using standard shell-supported ring data curves. Web and stiffener sizes and stiffener spacing are based on ET 2058 frame member sizes.

Pump-Fed Stress Analysis



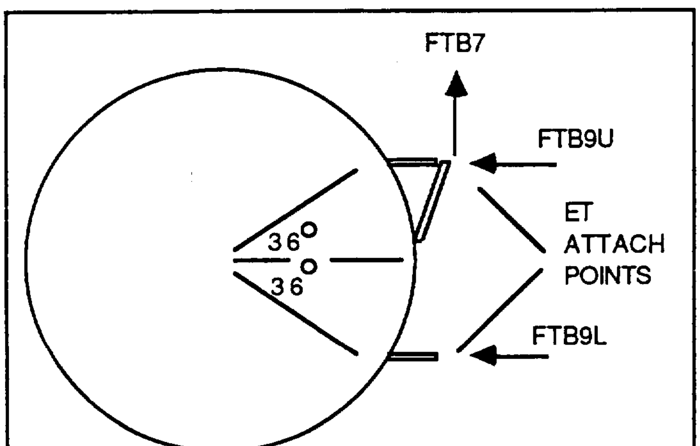
FRAME LAYOUT



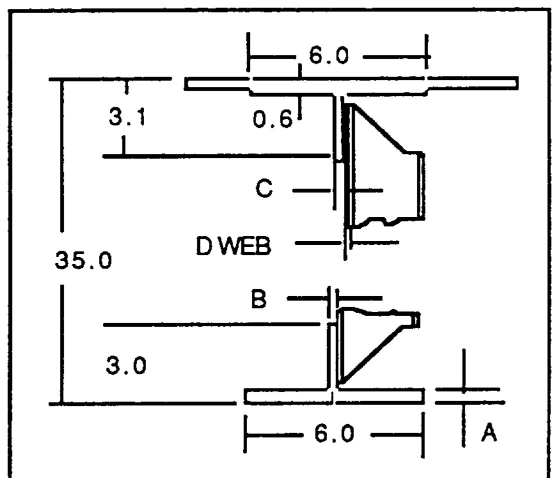
FRAME LOCATION

FRAME DIMENSIONS				
ZONE	CHORD DIM'NS			Web
	A	B	C	D
1	.5	.375	.375	.22
2	.4	.3	.3	.136
3	.4	.3	.3	.08
4	.35	.275	.3	.08
5	.35	.275	.3	.121
6	.4	.3	.3	.121
7	.4	.3	.3	.136

WEB STRESS		
ZONE	fS(WEB) KSI	V(MAX) KIPS
1	25.6	180
2	27.6	120
3	15.6	40
4	23.4	60
5	20.7	80
6	12.9	50
7	23.0	100



ET AFT ATTACH POINT POSITIONS



FRAME SECTION

L/O COND LOADS KIPS (ULT)		
FTB9L	-167	197
FTB9U	-347	157
FTB7	205.5	-130.5

CHORD STRESS				
ZONE	M IN-KIPS	N KIPS	fT MAX KSI	fC MAX KSI
1	5830	120	76.4	-31
	2747	-125	23.6	-36
2	2200	230	68.8	9.2
3	1500	-165	9.6	-36.6
4	2500	-97	30.3	-40.3
5	1200	73	40.0	-2.6
6	3000	170	68.7	-6.5
7	1500	-120	15.7	-30.5

JC2-LRB-5-2

<u>Frame XB 1513</u>

Pump-Fed Stress Analysis

Nose Cone

The Pump Fed LRB Nose Cone is similar to that for the Pressure Fed LRB discussed in section 7.5.1.2, allowing for necessary differences caused by the greater diameter of the Pressure Fed LRB. No separate analysis has been carried out at this time.

Pump-Fed Stress Analysis

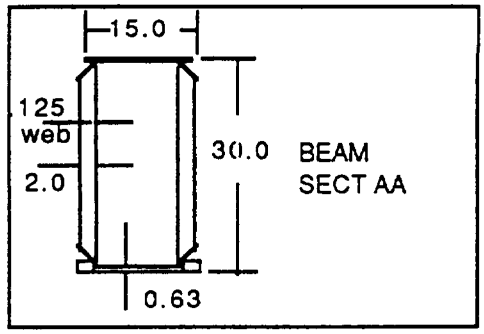
Forward Skirt

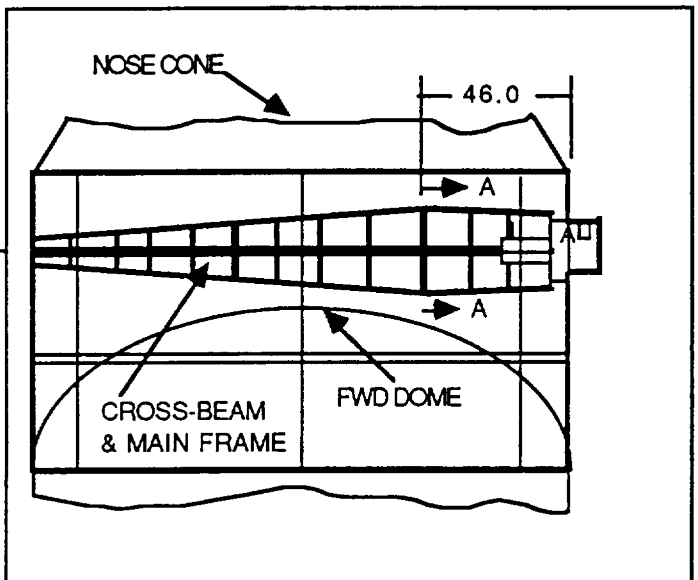
The Forward Skirt serves to connect the Nosecone to the LO2 Tank, and to transfer the forward ET/LRB Interface loads to the LRB.

The Forward Skirt is modelled after the ET Intertank, and uses a crossbeam to react the moment from the forward ET/LRB interface longitudinal (X - direction) and transverse (Z - direction) loads caused by the offset of the load transfer point from the LRB shell wall. The direct loads are reacted by a tapered thrust panel with a maximum thickness of 2.0 inches and reinforced by longitudinal stiffeners. The skirt contains 2 intermediate frames, one of which lies in the same plane as the crossbeam and assists in distributing interface loads to the shell, and 2 end flanges by which the skirt is bolted to the LO2 tank and Nosecone. The crossbeam is of tapered built-up box section, the frames built-up I section and the shell monocoque. The configuration used was chosen as easier to fabricate, given existing ET Intertank experience, than the alternative Longeron/Barrel concept considered.

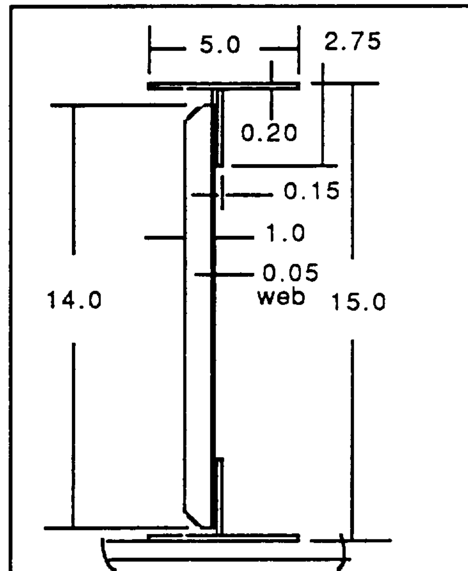
Pump-Fed Stress Analysis

BA Loads 0 PSI in LO2 Tank		BA Loads 40 PSI in LO2 Tank	
Max Stress (KSI)	Min Stress (KSI)	Max Stress (KSI)	Max Stress (KSI)
35.0 27.0	-31.0 -41.0	35.0 27.0	-31.0 -41.0

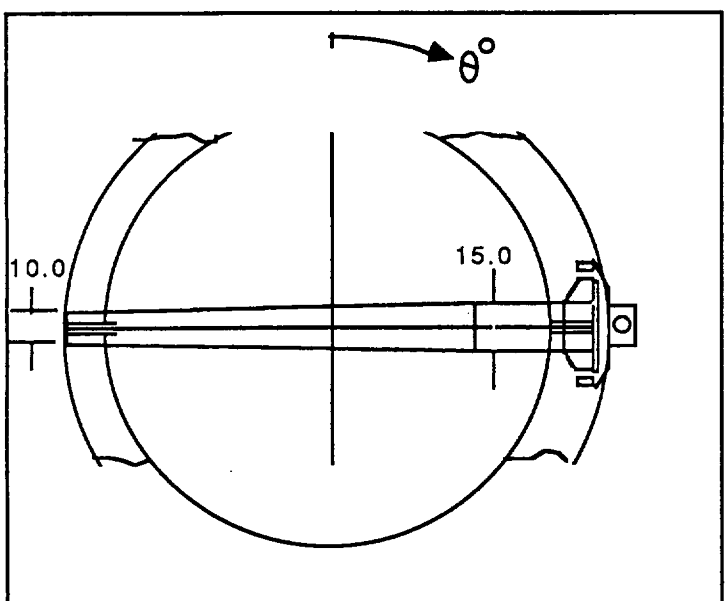




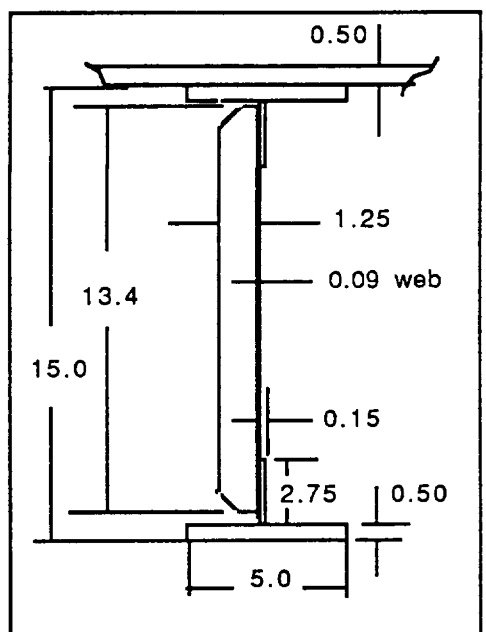
FORWARD SKIRT ARRANGEMENT



MAINFRAME SECT 20° - 340°



LONGITUDINAL VIEW



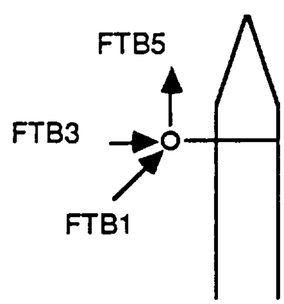
MAINFRAME SECTION 350° - 20°

<u>Forward Skirt ~~--Pump-Fed:~~</u>
<u>Cross Beam & Main Frame Design Data</u>

Pump-Fed Stress Analysis

Finite Element Analysis Of Forward Skirt

A preliminary finite element model of the forward skirt was created and analyzed using NASTRAN. The forward skirt model consisted of the outer shell including the thrust panel and extended to include part of the LO2 tank. The outer shell of the skirt was modelled using plate/shell elements and the frames were represented using beam elements. The forward skirt was constrained at a section approximately 400 inches below the ET/LRB forward interface so that the boundary conditions had minimal effect on the stresses in the region of interest. This structure was analyzed for Ultimate Boost Ascent (BA) loads. Von Mises stresses for this condition are shown below. Case 1 is for no internal pressure in the LO2 tank. Case 2 includes ullage pressure.

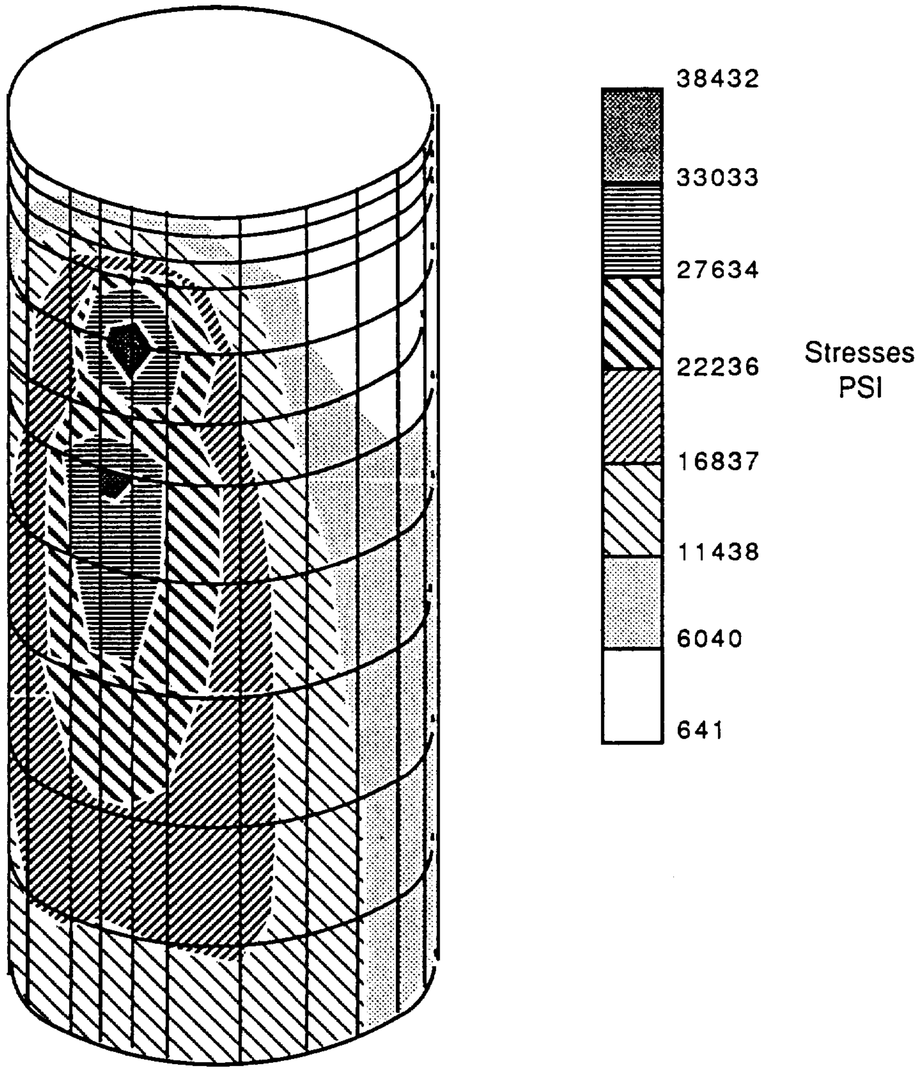


Load Case	Fwd ET/LRB Attachment Loads			LO2 Tank Ullage (psi)
	FTB5 (kips)	FTB3 (kips)	FTB1 (kips)	
1	-2070	152.5	8.8	0.0
2	-2070	152.5	8.8	40.0

Pump-Fed Stress Analysis

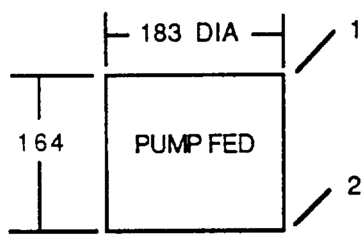
Forward Skirt

Von Mises Stresses in Skin And Thrust Panel (Load Case 2)



Pump-Fed Stress Analysis

The intertank is of welded monocoque construction, consisting of 120 degree segments and end attachment flanges. Shell thickness is 0.5 inches at the forward end and 0.55 inches at the aft end. Weld joint thickness is the same as that of the shell, i.e. there are no raised weld lands. Penetrations will be designed in as needed, and will require local reinforcement round the cutouts. The LRB needs a gauge of 0.5 on a stiffness basis, and this meets structural design requirements as noted above. The structural design conditions for the intertank are the Max Pitchover and Boost Ascent conditions, which induce compressive longitudinal - i.e. N(X) - loads which design the shell in buckling.



NX LOADS & BUCKLING MARGINS				
LOC	COND	N(X) - KIPS/IN	t - IN	M.S.
1	# 2	-9.5	0.5	0.06
2	# 2	-11.2	0.55	0.12

COND #2 = ON PAD; MAX PITCHOVER - PUMP FED

MARGINS FROM SHELL LONGITUDINAL TENSION LOADS $>$ 1.0

Intertank

Pump-Fed Stress Analysis

Aft Skirt

The basic dimensions and construction of the aft skirt are shown on the Aft Skirt Geometry sheet. The thickness of the upper cylinder is 0.65 inches and that of the cone is 0.7 inches. The shell is of welded plate segments. The engine mounting platform is situated 89.2 inches above the base, and 4 equi-spaced thrust posts run from this level to the cone-cylinder intersection level to transfer the engine thrust loads into the shell wall. The platform ties the posts together and provides stiffness when the thrust loads are vectored.

Frames are included at 4 levels:
1 - top
2 - cylinder/cone transition
3 - engine mounting platform
4 - bottom

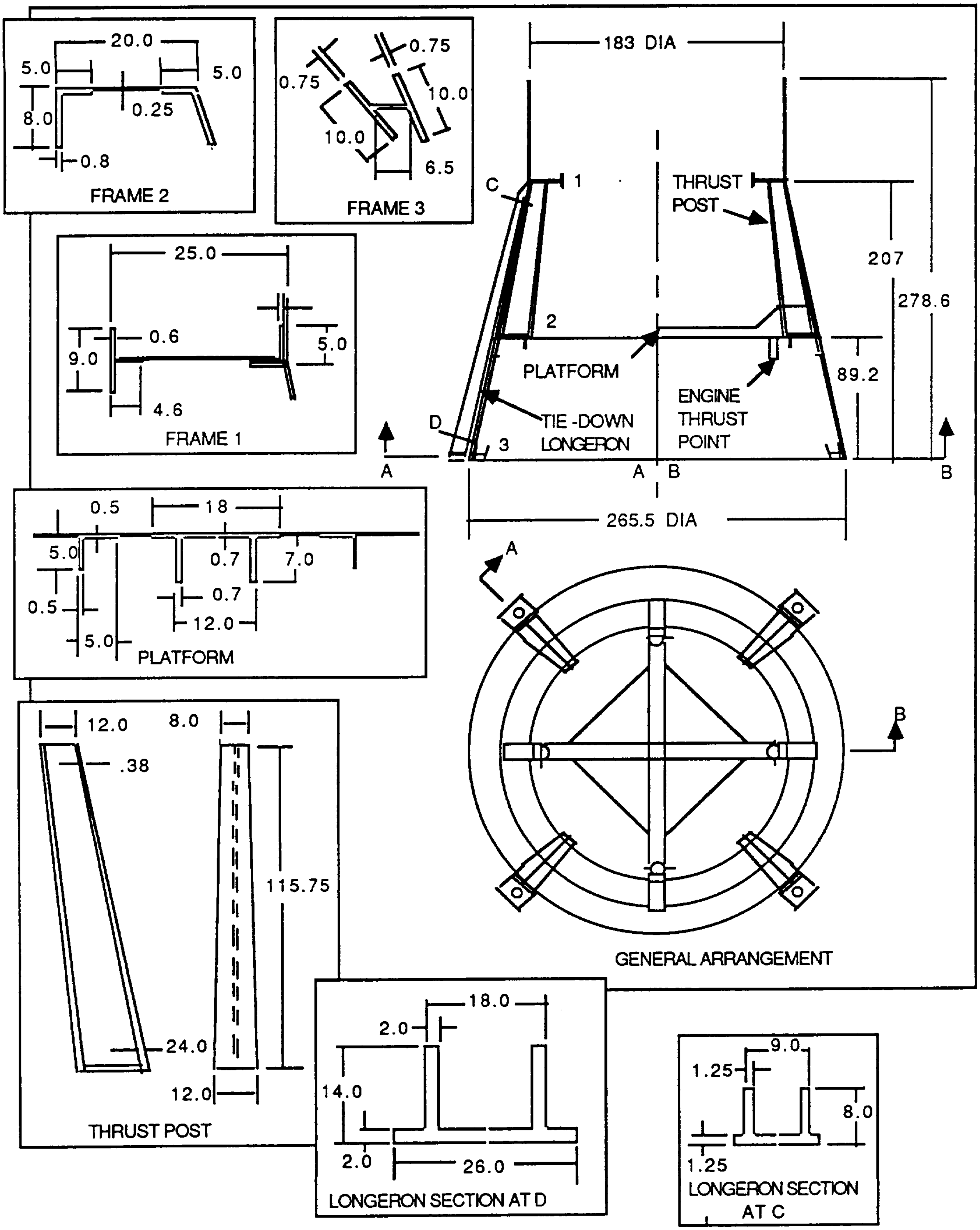
Kick loads from engine thrust are reacted by frames 2 and 3. Frame 2 also reacts kick loading from N(x) due to cylinder/cone transition. Frame 4 reacts kick loads from load transfer into the ground hold-down posts, and all frames assist in maintaining shell circularity.

4 forged tapered longerons welded into the shell are equi-spaced between the thrust posts and run from the base to the cylinder/cone transition. These longerons transfer loads from the shell to the ground hold-down posts prior to lift-off, and contribute to the overall stiffness of the shell.

3 conditions provide the design loads for the aft skirt: Max Pitchover, LRB Firing (Pre-Release), and Lift-Off.
Longerons are designed by the maximum compressive loads arising from condition 1, which also gives max buckling N(x) loads in the adjacent shell. Condition 3, with vectored thrust, gives the design loads for the thrust posts and platform, as well as buckling loads in the shell adjacent to the posts. Condition 2 gives tension loads between the engine thrust posts and platform and tie-down points, but results in less tension tie-down post load than the maximum from condition 1.

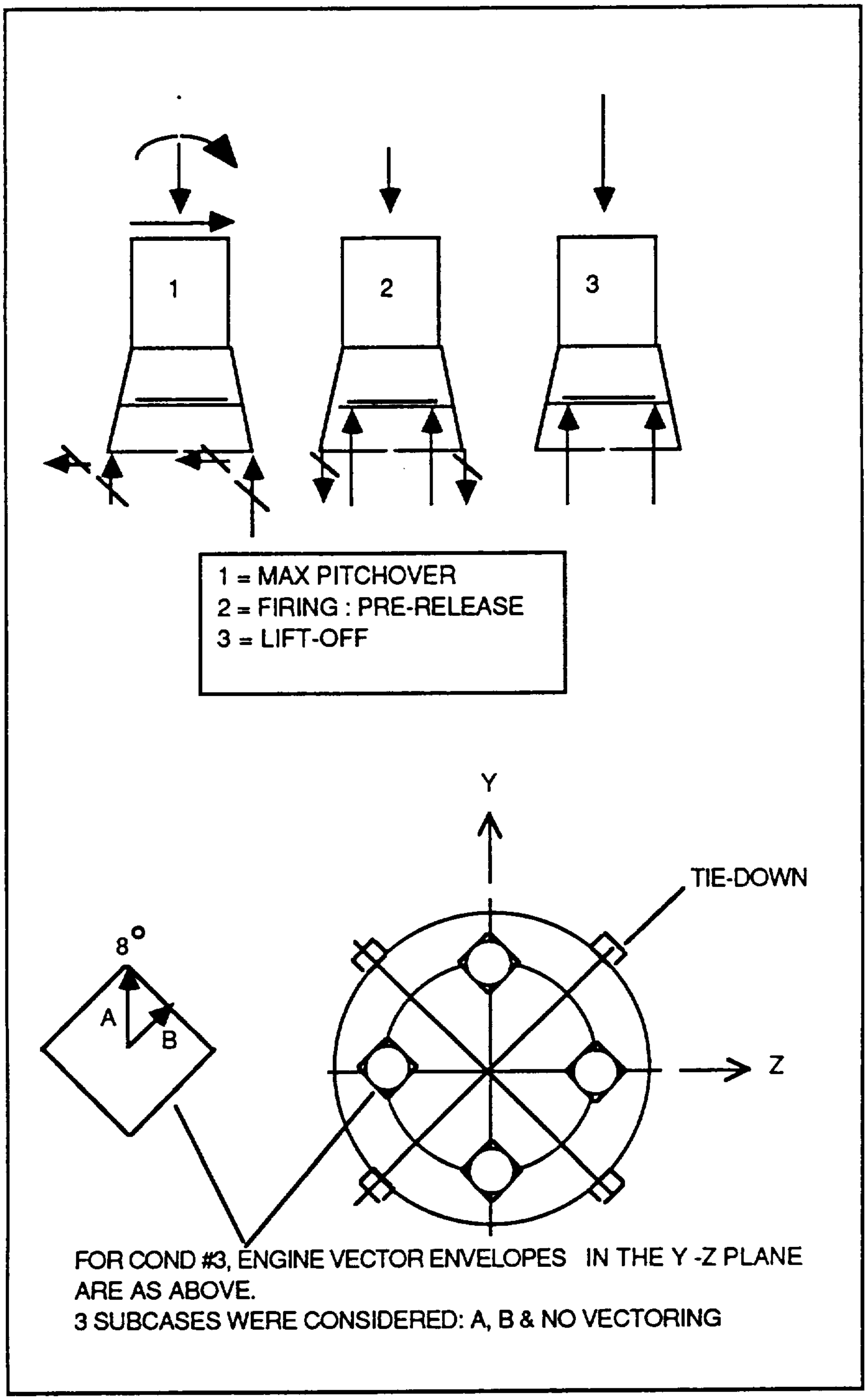
Condition 3 is taken as covering skirt loading for the duration of LRB flight, and the temperature assumed as 300 deg F.

Pump-Fed Stress Analysis



Aft Skirt Geometry Design Data

JC2-LRB-9-2



Aft Skirt Load Conditions

Pump-Fed Stress Analysis

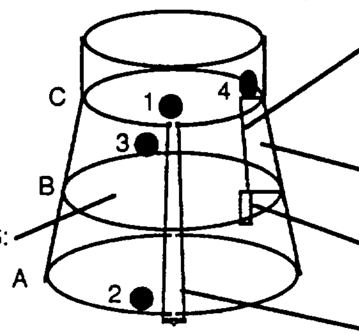
FRAME STRESSES		
FRAME	fT max	fC max
A	22.1	-35.3
B	50.2	-52.6
C	8.4	-52.2

STRESSES: KSI
SHELL LOADS: KIPS/IN

2

SHELL LOADS AND MARGINS				
AREA	t	Nx	Nxy	M.S
1	.65	-14.2	.95	.25
2	.8	-7.9	7.5	.17
3	.7	-12.0	6.1	.22
4	.65	-12.1	10.9	.33.

2 EFFECTIVE PANEL THICKNESS TAKEN AS 0.8 DUE TO TAPER-OUT OF LONGERON



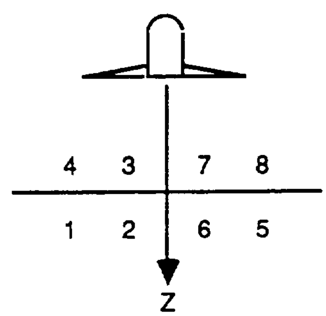
THRUST POST INNER CHORD
fC = -45.2
Fc(ALL) = -56

WEB
fS = 25.5

LOAD POST

PLATFORM CROSS-STIFFENERS:
1.5 KSI +/- 44.8 BENDING
PLATFORM EDGE-STIFFENERS:
-21 +/- 62.0 BENDING
(BENDING TO BE REDUCED BY REVISING LOAD POST/THRUST POST INTERCONNECTION)

TIE-DOWN LONGERON
fC = -47.7
Fc(ALL) = -55
(PIN-END STRUT BETWEEN FRAMES)



MAX TIE-DOWN POST LOADS - KIPS			
	F(X)	F(Y)	F(Z)
LOAD	1771	117	31
POST	6	1	4
LOAD	-964	-106	-103
POST	8	5	2
+X = COMPRESSION IN POST			

Aft Skirt Loads & Stresses

Pump-Fed Stress Analysis

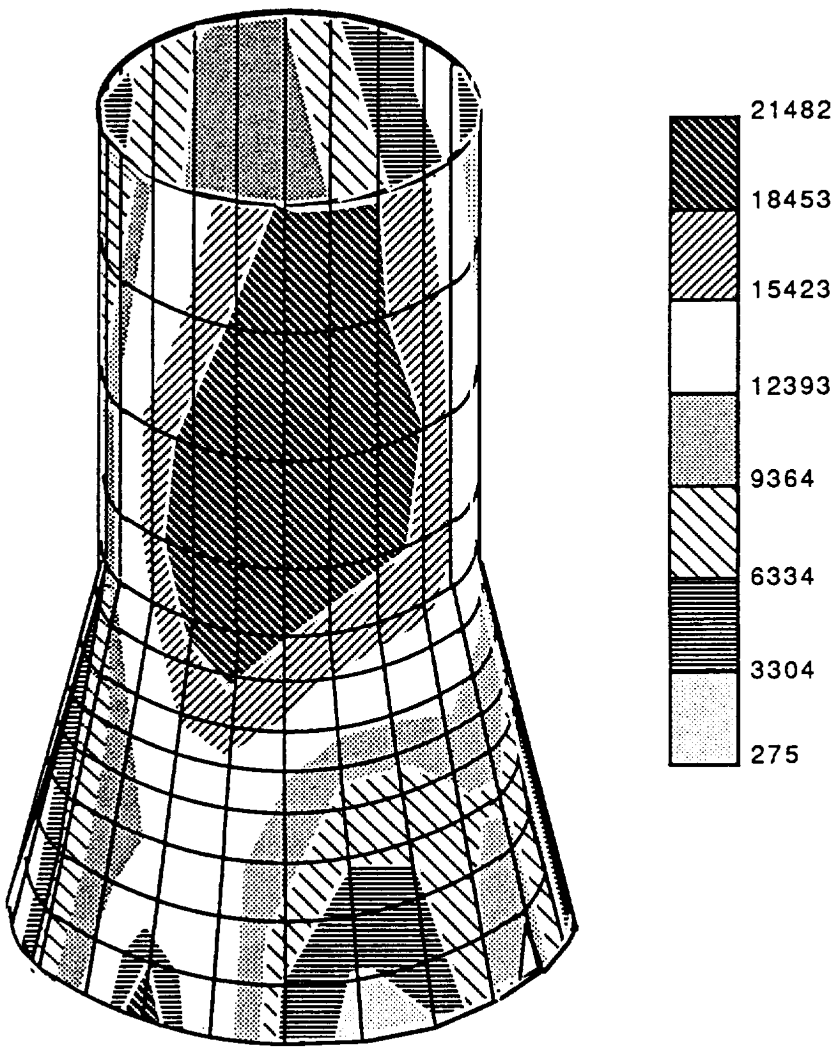
Finite Element Analysis of Aft Skirt

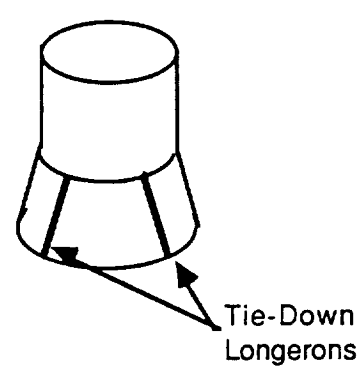
A preliminary finite element model (FEM) of the aft skirt was created and analysed using NASTRAN. The model consists of the outer shell, frames, thrust posts, tie-down longerons and engine mounting platform, using plate, shear, bar and rod elements as appropriate. The model was extended approximately 130 inches above the skirt/RP-1 tank interface so that boundary conditions had minimal effect on the stresses in the regions of interest. The structure was analyzed for the conditions shown on page 9 - 3, being restrained at the lower ground attachment points for condition #1, and at the upper boundary for conditions #2 and #3. Von Mises stresses for the shell are shown for condition #1 on page 9 - 6. Key maximum values from the analyses are quoted on page 9 - 4.

Pump-Fed Stress Analysis

Aft Skirt Nastran Plot

Vo Mises Stresses(PSI) - Max Pitchover Condition



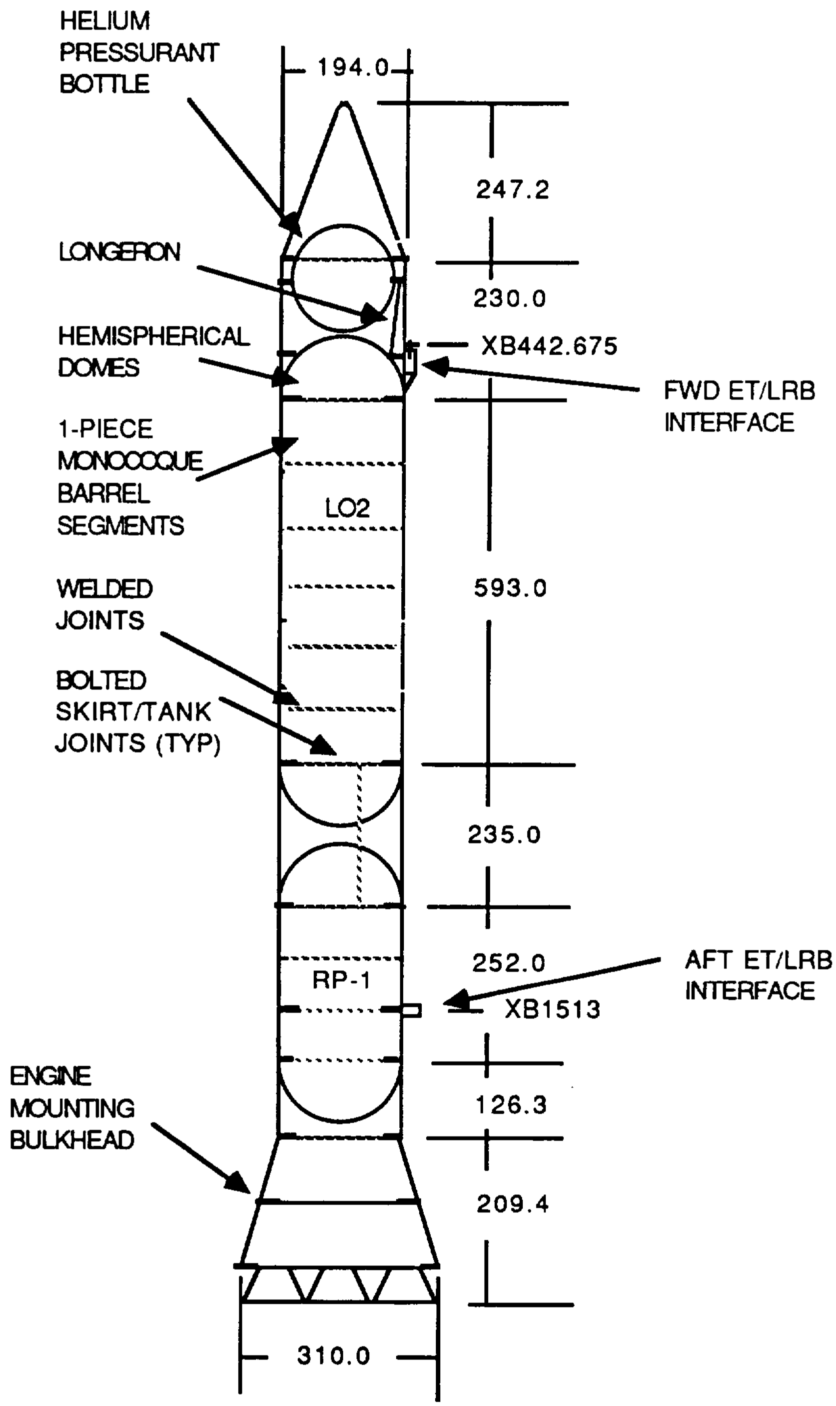


JC2-LRB-9-6

Pressure Fed Stress Analysis

Index

Pressure-Fed Stress Analysis



Structural Arrangement

Pressure-Fed Stress Analysis

Basic Data

Criteria (Ref: LRB CEI Specification - Rev 1, April 1988) :-
Safety Factors:
Ultimate = 1.25 (static and well-defined loads)
1.40 (dynamic and aerodynamic loads)
Proof = 1.10 (Min.)

Frame minimum stiffness requirements were obtained from Shanley - 'Weight-Strength Analysis of Aircraft Structures' - Equation 3.5

$(EI) = \frac{C_f M D^2}{L}$ where:

E = Frame Modulus
I = I of Frame Cross-Sect
L = Frame Spacing
D = Cylinder Diameter
C = 1/16000
M = fI/R
f = Max Cyl Stress from Bending + Axial Loads

The following values were taken as the best preliminary estimates available at time of analysis

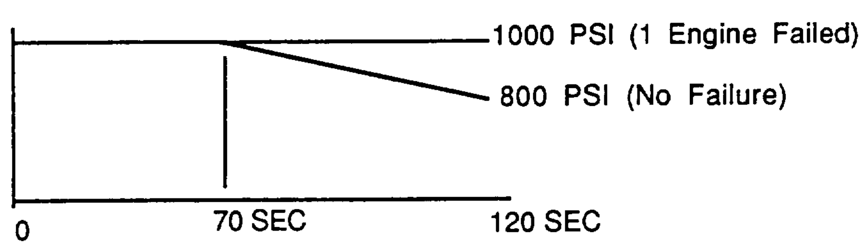
Properties of Weldalite TM 049:

	R.T.
Ftu (KSI)	100
Fty (KSI)	95
Weld Fall (KSI)	45.0
E 1000 (KSI)	11.3

Property Variation With Temperature						
°F	-297	R.T.	200	250	300	320
% R.T.	1.15	1.0	.95	.92	.90	.88

P(Ullage) Max Net = 1000 PSI

Ullage Pressure vs. Time Curves are approximately:



1 Engine Failed is taken as Tank Design condition

Pressure-Fed Stress Analysis

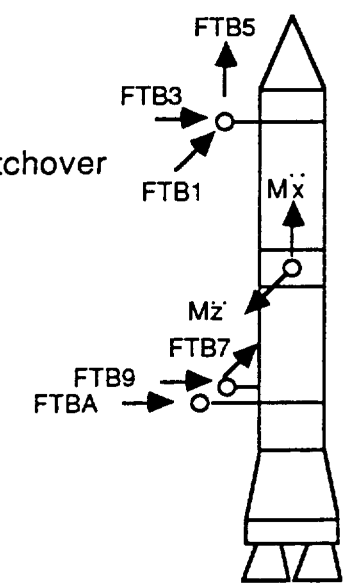
Loads = KIPS (ULT)
Loads on L.H. side of vehicle are shown
Loads on R.H. side are identical

FTB	3D REV4/REV5 LOADS		PRELIMINARY LRB STUDY LOADS - REV1 PUMP FED				PRESSURE FED				SRB RIGID BODY ANAL	
	MAX	MIN	MAX		MIN		MAX		MIN		MAX	MIN
1	285.4	-288.8	3	247.5	3	-172.5	8	252.5	8	-167.5	296.3	-123.8
3	296.5	-122.3	3	220.0	3	-60.0	8	200.0	8	-80.0	225.0	-55.0
5	223.3	-2205.6	-	-	5	-2069.0	-	-	10	-2066.0	-	-
7	346.1	-319.8	3	205.5	3	-130.5	8	210.5	8	-125.5	172.0	-164.0
9U	302.1	-248.4	3	157.0	3	$\boxed{-347.0}$	8	160.8	8	$\boxed{-343.3}$	154.0	$\boxed{-350.0}$
A	414.0	-353.8	3	197.0	3	-167.0	8	213.3	8	-150.8	196.0	-168.0

Load Condition Key:

6 - Press Fed - On Pad - Gravity Loads Only
7 - Press Fed - On Pad - Gravity + SSME's - Max Pitchover
8 - Press Fed - Lift Off
9 - Press Fed - Max Q
10 - Press Fed - Boost Ascent (BA)

Conditions 1 through 5 are for the Pump-Fed vehicle.



Interface Loads - Ultimate

Pressure-Fed Stress Analysis

Ultimate Bending Moment & Nx Diagrams

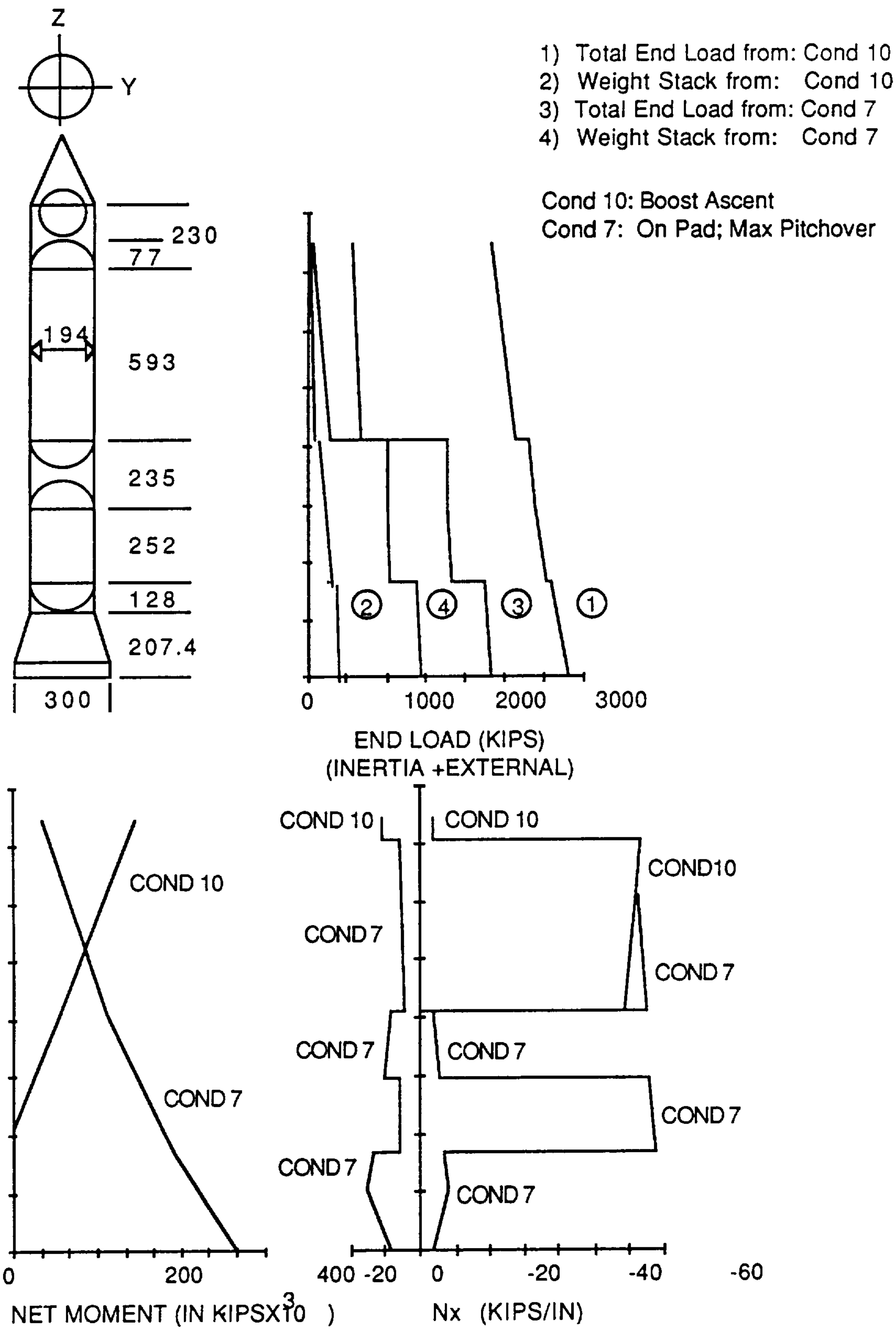
A loadset of 5 conditions is used for LRB design:

1) On Pad
2) On Pad; Max Pitchover
3) Lift-Off (L/O)
4) Max Q
5) Boost Ascent (BA)

Due to the predominating effect of ullage pressure on tank wall axial load, condition 1 is the only condition to give net axial compression in the tank wall. Condition 2 produces large cantilever moments about the base in the tie-down position, while condition 5 gives large moments at the forward ET attach point due to the LRB thrust reaction, which is maximum at BA. These moments combine with ullage pressure to give max axial tension in the tank walls. Ullage is taken as 1000 psi max (limit).

The maximum moments shown are the resultants of the My & Mz values at each station, and hence their angular position varies with station along the tank. Also, max moments from the different conditions have different angular positions at any given station.

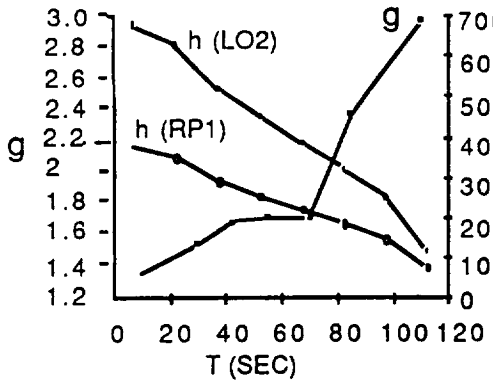
Pressure-Fed Stress Analysis

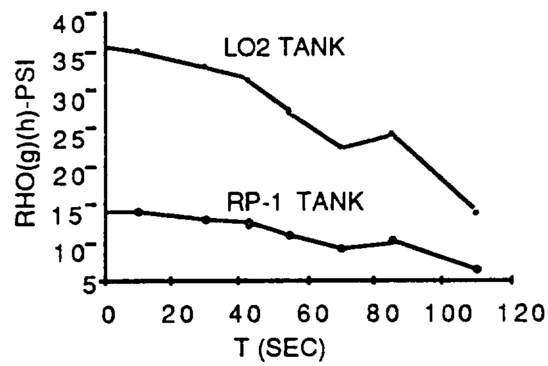


Ultimate Bending Moment & N(X) Diagrams

JC2-LRB-2-5

Pressure-Fed Stress Analysis





h = Height of liquid above dome bottom (in.)
RHO = Liquid Density (lb/cu. in.)
h = Liquid height above tank bottom (in.)
g = 32.2 ft./sec./sec.

The above graphs for the pump-fed LRB show that the maximum values of rho(g)(h), i.e. head pressure at tank bottom, occur at Lift-Off. A similar pattern holds for the Pressure-fed LRB.

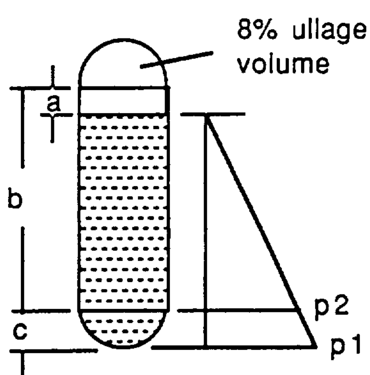


Fig 1

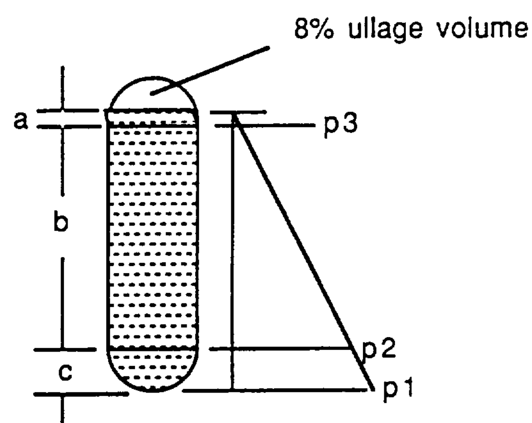


Fig 2

Values at Lift-Off

	Pressure-Fed	
	LO2 Tank	RP1 Tank
Ref. Fig.	2	2
a (in)	7	34
b (in)	593	252
c(in)	97	97
rho (lb/in^3)	.0411	.0293
g [1]	1.57	1.57
p1 (psi)	45.0	17.6
p2 (psi)	38.7	13.1
p3 (psi)	0.5	1.6

The above table gives Limit values of Head Pressure P at stations shown

[1] From Loadsets of 3/21/88 & 3/25/88

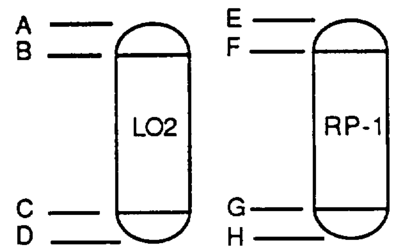
Tank Head Pressures

Pressure-Fed Stress Analysis

2 conditions are considered for maximum tank pressure:-
1) Lift-Off, where tank head pressures are maximum
2) Pre-Release, where tank head pressures are virtually zero, and only ullage pressure is considered, but wall temperatures are maximum, and material strength properties have suffered maximum reduction.

Press-Fed Ullage Pressure (Limit) = 1000 psi
(Engine Failure Condition requires approximately this value throughout LRB flight)

S.F. = 1.25
LO2 density = .0411 lb/cu. in.
RP1 density = .0293 lb/cu.in.



Lift-Off

SECT	P	T	NOTE	K	P(EQ)
A	1250	RT	1	1.0	1250
B	1250	RT	1	1.0	1250
C	1298	-297	2	1.15	1129
D	1306	-297	2	1.15	1135
E	1250	RT	1	1.0	1250
F	1252	RT	3	1.0	1252
G	1266	RT	3	1.0	1266
H	1272	RT	3	1.0	1272

Pre-Release

SECT	P	T	NOTE	K	P(EQ)
A	1250	250	3	.93	1344
B	1250	250	3	.93	1344
C	1250	RT	3	1.0	1250
D	1250	RT	3	1.0	1250
E	1250	320	4	.88	1420
F	1250	320	4	.88	1420
G	1250	200	3	.95	1316
H	1250	200	3	.95	1316

P = Ult Pressure (Ullage + Head) - PSI
T = Wall Temp (Deg. F)
K = Material Strength Temperature Factor
P(EQ) = P/K

Notes:-
1 Pressurized by ambient temperature helium until L/O
2 Propellant temperature
3 Estimated values
4 From Thermal Group data, assuming ullage temp = 700 Deg. R

Max Ultimate Pressures

Pressure-Fed Stress Analysis

The tanks are proofed by water at room temperature. The values shown assume the tanks are suspended at the upper dome/barrel intersection level since this slightly reduces the required pressure compared with base mounting. The LO2 tank proof pressure is set by the pressure needed to proof the upper dome/barrel circumferential weld against longitudinal loads, and the RP-1 tank proof pressure by the pressure needed to likewise proof the lower dome/ barrel intersection. The value shown for barrel N(x) proof pressure is that value of uniform internal pressure in the tank which would produce the same longitudinal load/in in the barrel as the proof head pressure with the tank suspended as shown. The higher pressure required at the forward dome intersection for N(x) proof in the LO2 tank reflects the higher N(x) load arising from tank bending at this position. Due to the proof pressures required on the above basis, the tank is overproofed for hoop loading. (There are no longitudinal welds in the pressure-fed tank barrels.) Pinch loads on the Aft LRB Support frame are not considered at this stage, and their simulation by mechanically applied loads may alter the scheme shown.

PROOF PRESSURES (P) AND RESULTANT STRESSES (F)

LOC	P REQ PSI	TO PROOF	FOR CONDITION	(PROOF) PSI		F(PROOF) KSI MEMBRANE		F(PROOF) KSI WELD	
				LONG WELD	CIRC WELD	LONG	HOOP	LONG	HOOP
A	1196	DOME WELDS	P(ULLAGE)	1229	1229	90.15	90.15	40.75	40.75
B	1258	CRC WELD AT B	NX(#10)	1233	1258	46.65	91.23	20.98	41.04
C	1073	CRC WELD AT C	NX(#10)	1255	1258	48.13	94.35	21.51	42.83
D	1100	DOME WELDS	P(TOT)#10	1259	1259	93.75	93.75	42.91	42.91
E	1250	DOME WELDS	P(ULLAGE)	1250	1250	87.65	87.65	39.27	39.27
F	1181	CRC WELD AT F	NX(#7)	1253	1265	44.52	88.01	20.00	39.53
G	1219	CRC WELD AT G	NX(#7)	1263	1265	47.28	94.17	21.25	42.33
H	1158	DOME WELDS	P(TOT) #8	1267	1267	92.88	92.88	41.99	41.99

PARENT METAL F(YIELD) = 95 KSI
WELD F(ALL) = 45 KSI

COND #7 = ON PAD; MAX PITCHOVER
COND #8 = LIFT - OFF
COND #10 = BOOST ASCENT

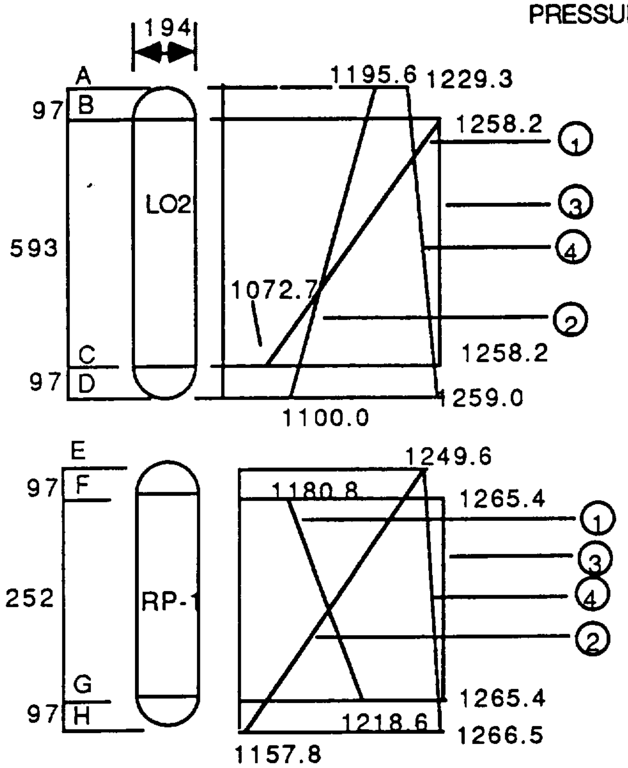
STRESSES IN KSI
PRESSURES IN PSI

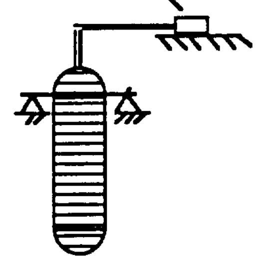
MEMBRANE & WELD THICKNESSES (INCHES)

POSITION	t(MEMBRANE)	t(WELD)
A	.66	1.46
B	1.30	2.89
C	1.28	2.82
D	.65	1.42
E	.69	1.54
F	1.37	3.05
G	1.29	2.87
H	.66	1.46

Proof Pressure

Pressure-Fed Stress Analysis





P3 IS THE EQUIVALENT UNIFORM INTERNAL PRESSURE TO PRODUCE THE SAME NX IN THE TANK WALL AS THE ACTUAL HEAD PRESSURE (RHO)(G)(H) WITH THE TANK SUSPENDED AS SHOWN

PROOF PRESSURES ARE SET BY THE REQUIREMENT OF CURVE 3 TO MEET CURVE 1 AT LEVEL C (LOXTANK) & CURVE 4 TO MEET CURVE 2 AT LEVEL E (RP-1 TANK)

1 REQU'D PROOF PRESSURE (BARREL - NX)
2 REQU'D PROOF PRESSURE (BARREL NY & DOMES)
3 PROOF PRESSURE (BARREL NX)
4 PROOF PRESSURE (BARREL NY & DOMES)

PROOF WITH WATER AT ROOM TEMPERATURE.
TANKS SUSPENDED AT LEVEL B (LOXTANK) & LEVEL F (RP1 TANK)

PROOF FACTOR = 1.10
PRESSURES = PSI

REQUIRED PRESSURES DERIVED ON ROOM TEMPERATURE EQUIVALENTS OF APPLIED LOADS

Proof Pressure

Pressure-Fed Stress Analysis

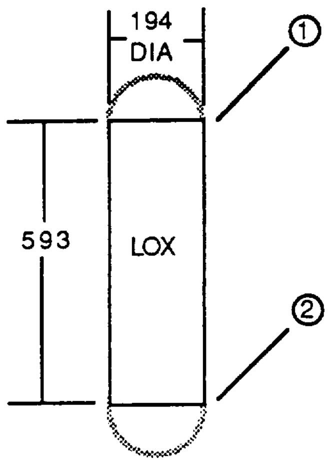
Barrels

The pressure-fed barrels are formed from flow-forged circular segments, 6 in the LO2 barrel and 3 in the RP-1 barrel, thus avoiding longitudinal welds. Shell thickness range from 1.28 to 1.37 inches and weld and weld land thicknesses from 2.82 to 3.05 inches. The XB1513 aft ET/LRB attachment frame is mounted between the 2nd and 3rd segment of the RP-1 barrel. Frames are also incorporated at the dome/barrel junctions.

Barrels are designed by the hoop loads (from ullage pressure plus propellant head) from the Lift-Off and Boost Ascent conditions. The max compressive longitudinal loads which arise in the Pump Fed tank are overridden in the Pressure-Fed tank by the high ullage pressure, so that net longitudinal tension results.

The On Pad - Unpressurized condition does not give sufficiently high longitudinal compression to be significant.

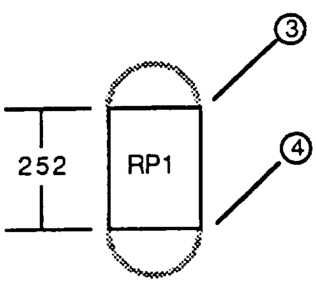
Pressure-Fed Stress Analysis



VALUES CORRECTED TO ROOM TEMP EQUIVALENTS

COND #8 = LIFT-OFF
COND #10 = BOOST ASCENT

PARENT ULT F(ALL) = 100 KSI
PARENT PROOF F(ALL) = 95 KSI
WELD F(ALL) = 45 KSI



THICKNESSES (IN)		
ZONE	PARENT	WELD
1	1.30	2.89
2	1.28	2.82
3	1.37	3.05
4	1.29	2.87

HOOP STRESSES & MARGINS							
				PARENT		WELD	
LOC	COND	S.F.	PRESSURE(PSI)	f(KSI)	M.S.	f(KSI)	M.S.
1	#10	1.25	1344	99.64	0.00	44.82	0.00
	PROOF	1.1	1233	91.23	0.04	41.04	0.10
2	#10	1.25	1298	97.73	0.02	44.36	0.01
	PROOF	1.1	1255	94.35	0.01	42.83	0.05
3	#10	1.25	1420	99.89	0.00	44.87	0.00
	PROOF	1.1	1253	88.01	0.08	39.53	0.14
4	#8	1.25	1333	99.59	0.00	44.76	0.00
	PROOF	1.1	1263	94.17	0.01	42.33	0.06

Barrels

Pressure-Fed Stress Analysis

XB1513 Frame

The Pressure Fed LRB XB 1513 Frame is similar to that for the Pump Fed LRB discussed in Section 6.5.1.2, allowing for necessary differences caused by the greater diameter of the Pressure Fed LRB, and no separate analysis has been carried out at this time.

Pressure-Fed Stress Analysis

Nosecone

The nosecone is ring-stiffened sheet construction, divided into 7 bays plus a nosecap by the rings. The skin thickness increases from cone apex to cone base and the ring cross-section areas increase in like fashion. The cone supports the forward separation motor package which delivers an aft and outward acting thrust relative to the External Tank. Numbering the rings as 1 to 8 from base to apex, the separation package is mounted at the ring 2 location on a bracket which spans between ring 1 and ring 3, which are sized to support the separation loads.

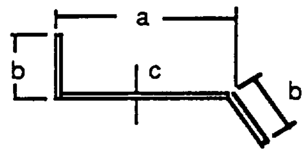
The cone is considered under 2 separate load conditions, i.e, Max Airload and Separation Loads. The air pressure has a sideways as well as axial component, and hence a given cone section is subjected to shear, axial compression and bending as well as direct pressure. The airload condition sizes the cone, except for rings 1 and 3 which are designed by separation loads as stated above. Cone dimensions are kept uniform circumferentially, i.e., an entire section is designed for the highest loaded point on the section . Maximum cone temperature is assumed to be 300 deg F.

Bruhn Sect C 8.20 (cone buckling under combined loads) is used for sheet sizing. The rings are taken as shell-supported under 1 bay-width of air pressure.

Separation loads are taken as point loads on frames 1 and 3 and the ring internal loads obtained from standard curves for shell-supported rings.

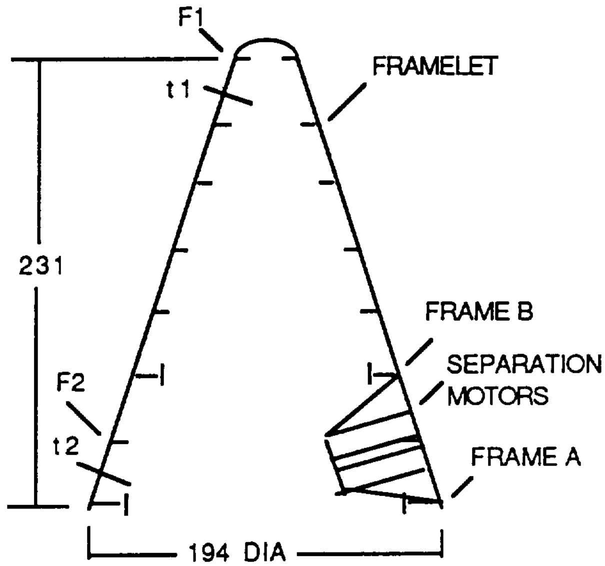
Pressure-Fed Stress Analysis

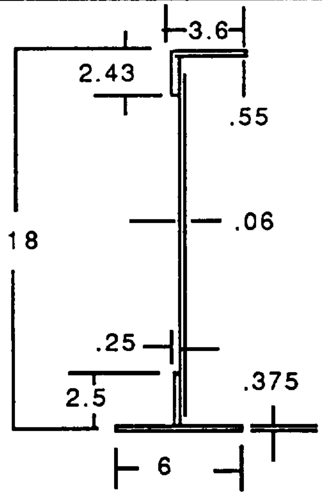
t1	.09
t2	.24

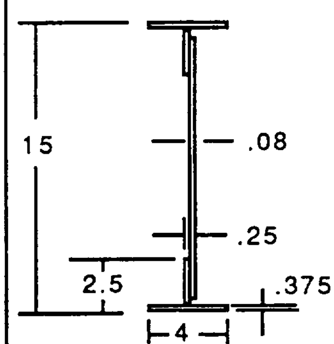


	a	b	c
F1	2	.75	.08
F2	5	1.5	.20

FRAMELETS



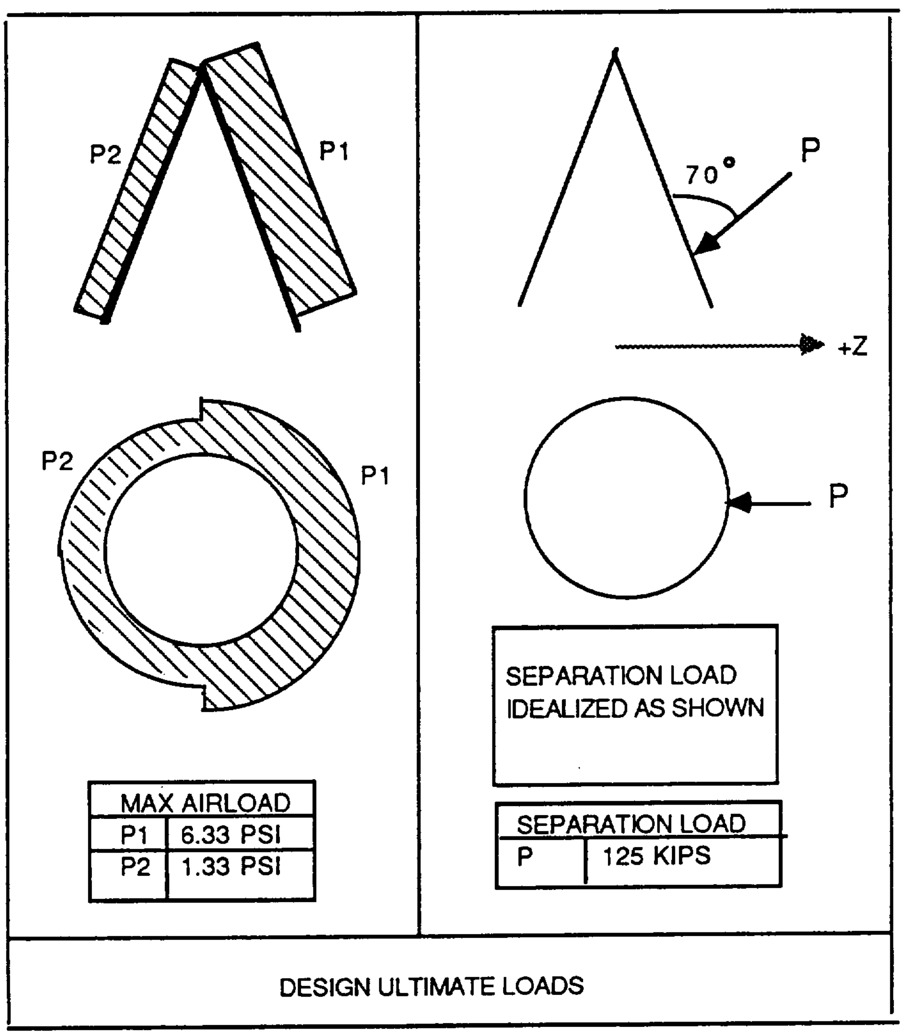




FRAME	A	B
M IN-KIPS	1322	839
N KIPS	-34.9	12.0
V KIPS	24.0	24.0
fC KSI	36.0	34.8
fT KSI	23.4	28.8
fS KSI	26.7	25.0

<u>Nose Cone Analysis Data</u>

Pressure-Fed Stress Analysis



CONE DESIGNED BY COMPRESSION, BENDING, SHEAR & BUCKLING LOADS FROM MAX AIRLOAD CONDITION

M.S.(BUCKLING) AT CONE BASE = 0.25

SKIN THICKNESS INCREASES FROM APEX TO BASE
FRAMELET CROSS-SECTIONS VARY IN LIKE FASHION

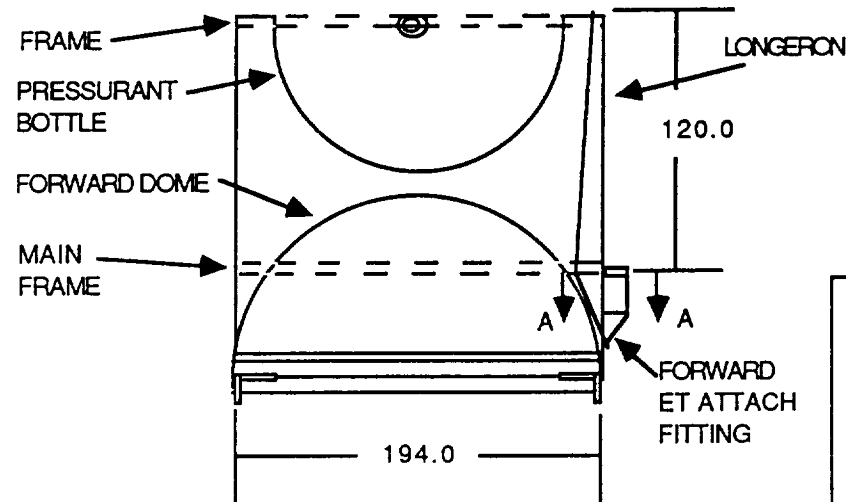
Nose Cone Analysis Data (Cont'd)

Pressure-Fed Stress Analysis

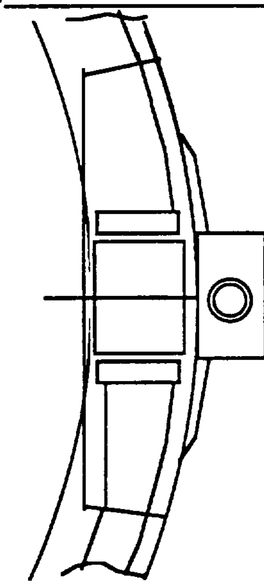
Forward Skirt:

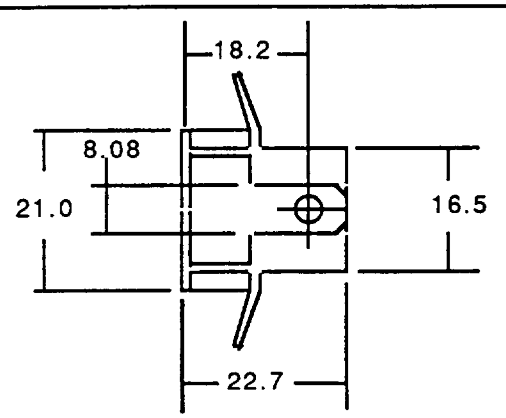
The Forward Skirt serves to connect the Nosecone to the LO2 tank and to transfer the forward ET/LRB Interface loads into the LRB. Due to the volume occupied by the Helium Pressure Bottle, incorporation of a crossbeam, as in the Pump-Fed Forward Skirt, was not feasible and a configuration similar to that used in the SRB was adopted. This consists of a ring-stiffened shell with a longeron spanning 2 of the rings. The longeron distributes the longitudinal (X direction) loads into the shell, and acts a beam to transfer moment, shear and torsion from Y and Z loads, and moment from the X load offset from the shell wall, into the supporting frames and hence to the shell. The Pressure Bottle is trunnion-mounted on support longerons mounted between the frames, and lying on the Z axis. The bottle is free to slip in the Z direction at one trunnion, thus allowing for thermal change. The longeron is of built-up box section, and the shell is monocoque. End flanges allow the skirt to be bolted to the Nosecone and LO2 Tank.

Pressure-Fed Stress Analysis



FORWARD SKIRT ARRANGEMENT





LONGERON SECTION AT A-A

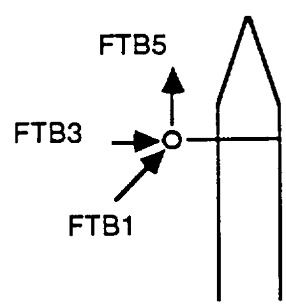
Part	Boost Ascent (BA) Loads			
	P(ullage) = 0		P(ullage) = 40 PSI	
	Max Stress KSI	Min Stress KSI	Max Stress KSI	Max Stress KSI
Longeron Top Frame LOwer Frame	10.45 42.0 11.07	-25.0 -23.0 -12.56	10.62 46.62 11.14	-24.67 -23.50 -21.88

<u>Forward Skirt</u>
<u>Longeron & Upper & Lower Frames Design</u>

Pressure-Fed Stress Analysis

Finite Element Analysis Of Forward Skirt

A preliminary finite element model of the forward skirt was created and analyzed using NASTRAN. The forward skirt model consisted of the outer shell including the thrust panel and extended to include part of the LO2 tank. The outer shell of the skirt was modelled using plate/shell elements and the frames were represented using beam elements. The forward skirt was constrained at a section approximately 400 inches below the ET/LRB forward interface so that the boundary conditions had minimal effect on the stresses in the region of interest. This structure was analyzed for Ultimate Boost Ascent (BA) loads. Von Mises stresses for this condition are shown below. Case 1 is for no internal pressure in the LO2 tank. Case 2 includes ullage pressure .

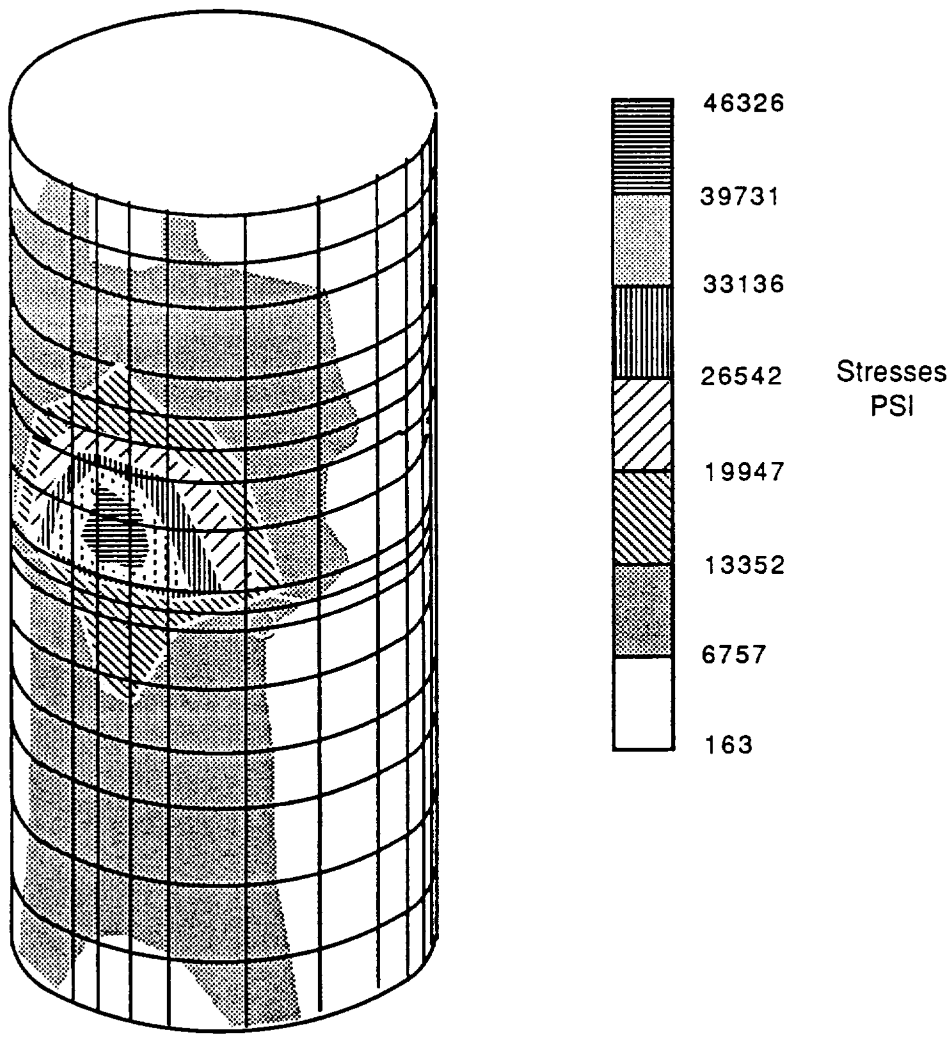


Load Case	Fwd ET/LRB Attachment Loads			LO2 Tank Ullage	He Bottle 'g' load (along X axis)
	FTB5 (kips)	FTB3 (kips)	FTB1 (kips)	(psi)	(kips)
1	-2070	152.5	8.8	0.0	-75.0
2	-2070	152.5	8.8	1250	-75.0

Pressure-Fed Stress Analysis

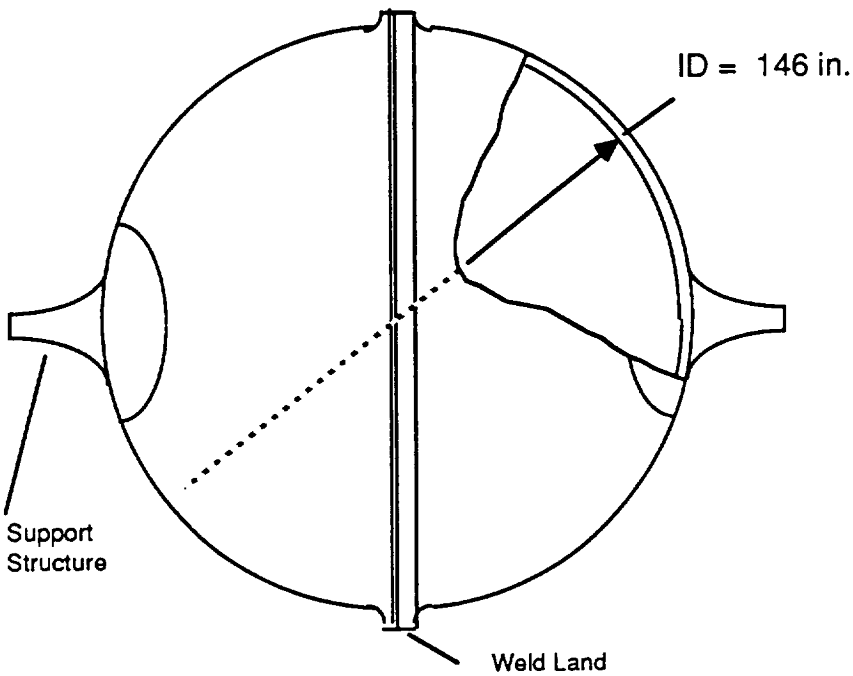
Forward Skirt

Von Mises Stresses in Skin and Thrust Panel (Load Case 1)



Pressure-Fed Stress Analysis

Helium Pressurant Tank



Requirements

	Thickness
Tank	1.74 in./ 3.3 in weld
TPS	3.0 in

Volume = 950 cu.ft.

Pressure = 3000 psi at 10 deg R ~ - 450 deg F
or 1100 psi at 600 deg R ~ 140 deg F

Ultimate F.S. = 2.0

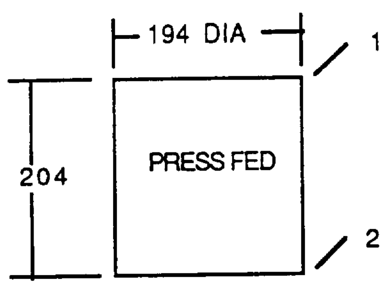
Material : Weldalite

Parent Material	Weld Material	Temperature
Ftu = 127.8 ksi	Ftu = 67.4 ksi	@ - 450 deg F
Ftu = 97ksi	Ftu = 46.1 ksi	@ 140 deg F

Pressure(psi)	f(Parent)ksi	M.S.	f(Weld)ksi	M.S
3000	127.8	0.0	67.4	0.0
1100	46.7	2.0+	24.7	0.87

Pressure-Fed Stress Analysis

The intertank is of welded monocoque construction, consisting of 120 degree segments and end attachment flanges. Shell thickness is 0.5 inches at the forward end and 0.55 inches at the aft end. Weld joint thickness is the same as that of the shell, i.e. there are no raised weld lands. Penetrations will be designed in as needed, and will require local reinforcement round the cutouts. The LRB needs a gauge of 0.5 on a stiffness basis, and this meets structural design requirements as noted above. The structural design conditions for the intertank are the Max Pitchover and Boost Ascent conditions, which induce compressive longitudinal - i.e. N(X) - loads which design the shell in buckling.



NX LOADS & BUCKLING MARGINS				
LOC	COND	N(X) - KIPS/IN	t - IN	M.S.
1	#7	-8.6	0.5	0.09
2	#7	-10.6	0.55	0.10

COND #7 = ON PAD; MAX PITCHOVER - PRESS FED

MARGINS FROM SHELL LONGITUDINAL TENSION LOADS > 1.0

Intertank

Pressure-Fed Stress Analysis

Aft Skirt

The Pressure Fed LRB Aft Skirt is similar to the Pump FEd LRB Aft Skirt discussed in Section 6.5.1.2, allowing for necessary differences arising from the greater diameter of the Pressure Fed LRB, and no separate analysis has been done at this time.